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Retrofitting the Future: Preserving Native Crops with Sustainable Greenhouse Technology

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Retrofitting the Future: Preserving Native Crops with Sustainable Greenhouse Technology

An Interactive Qualifying Project submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements of the Degree of Bachelor of Science.

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Abstract

This Interactive Qualifying Project focuses on farming sustainably with greenhouses using new technologies and concepts. Sustainable greenhouse designs could allow indigenous people of northern New Mexico to preserve their native crops in an efficient way. The team compared the Santa Fe Indian School and Tesuque Pueblo greenhouses to sustainable structures around the country. Next, the team assessed these greenhouses for inefficiencies and established appropriate insulation retrofits. Through research and experimentation on a small-scale hoop house, the team was able to propose ways the Santa Fe Indian School and Tesuque Pueblo could make their own greenhouses more sustainable and energy efficient. The team then developed a sustainable greenhouse design suitable to the Santa Fe area by adapting existing energy-efficient designs from elsewhere in the country to the specific climate and culture of New Mexico, incorporating local building materials. Finally, the team produced an educational website hosting a narrated video and interactive guide explaining how to build greenhouses and make them more efficient. The website also includes important information on modern greenhouses to empower the Santa Fe and Tesuque communities with essential tools to farm more sustainably.

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Executive Summary

Figure 1: Map of Santa Fe with Tesuque and Indian School

The Santa Fe Indian School and Tesuque Pueblo, both located in Santa Fe, New Mexico have been utilizing greenhouse farming to extend their growing season and to combat the changing climate of the southwest. Over the past 40 years, global average temperatures have increased approximately 1.1 degrees Fahrenheit. By the year 2100, global temperatures are expected to rise by another 2 to 11.5 degrees Fahrenheit. Currently, the Santa Fe area is in a state of drought and with these predictions it can be expected that droughts will continue and likely get worse. The weather in New Mexico is very erratic and unpredictable, creating challenges for local farmers. For example, there are usually frosts in the middle of April that kill many of the crops planted outdoors. Since agriculture is an important part of the pueblo culture, protecting local crops is vital as many are at risk of extinction and so it is important that people do all they can to preserve them. Many Santa Fe cultural crops, such as tobacco, are used in traditional dances and ceremonies in the pueblos. Crop preservation is necessary in order to keep these traditions alive.

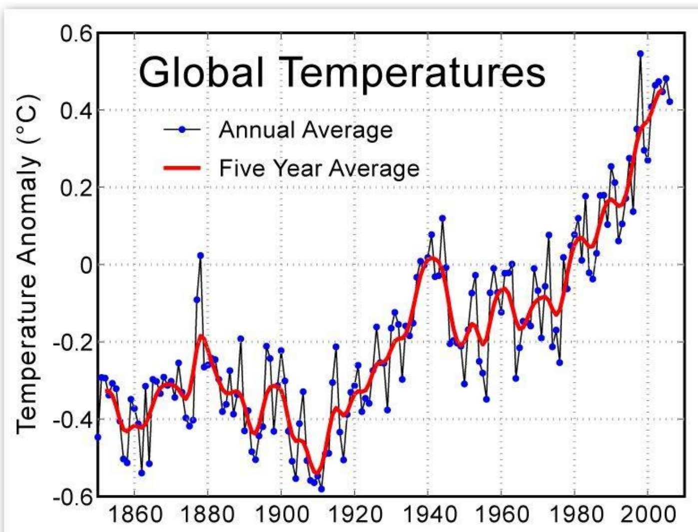

Figure 2: Trend of Increasing Global Temperatures

When faced with a volatile climate such as that of New Mexico, one solution for farmers is to modify the seedlings so that they can survive harsher weather conditions. Genetically Modified Organisms (GMO's) are one way to allow crops to grow in harsher climates. Corn for example, is a crop used in many traditional Mexican meals; however 86% of all corn produced in the United States is genetically modified. Therefore, GMO's are not a way of preserving traditional cultural crops.

If farmers do not want to change their seedlings to make them resistant to harsher climates, the other solution is to change the climate to meet the needs of the crops. The main way to do this is to build greenhouses. There are two types of greenhouses: passive and active. Passive greenhouses do not require any energy to power and utilize natural convection currents to heat or cool and sometimes require manual labor to open and close windows and vents. Active greenhouses typically have heaters and coolers on the inside that are powered by gas or electricity. These are not as energy efficient but can maintain a steadier interior climate. In recent years, new sustainable greenhouses, such as Larry Kinney's greenhouse in Boulder, CO, have been developed. Sustainable greenhouses combine passive and active technology. A very efficient greenhouse focuses on passive technology, but uses some energy to open and close vents. Kinney's greenhouse has ground insulation, light shelves, exclusively south facing windows, and automated vents that open or close depending on the temperature. He powers his entire greenhouse with only a car battery. Recently, greenhouses have begun to move in this sustainable direction.

Figure 3: Larry Kinney's Sustainable Greenhouse Design

The Santa Fe Indian School and Tesuque Greenhouses are active greenhouses and are extremely inefficient. In order to increase the efficiency of these greenhouses, the team established the following objectives:

1. Assess the Santa Fe Indian School and Tesuque Greenhouses
2. Identify Appropriate Retrofits for these Greenhouses
3. Design an Ideal Greenhouse for Santa Fe, New Mexico
4. Produce Educational Resources

The first objective was completed using a data logger and sensors that record temperature, humidity, and light intensity. The team put the sensors in both the SFIS and Tesuque greenhouses for multiple days. We then analyzed the data to determine the inefficiency of the greenhouses. The structures of both greenhouses are similar, but are different in their structural materials. Both greenhouses have similar insulating values, but have different degrees of light transmission. The SFIS greenhouse structure has straight walls and an arched roof whereas the Tesuque greenhouse only has one large arched roof. Apart from the structural and material differences, the greenhouses are nearly equally inefficient and overuse the heaters and coolers. Figure 4 shows how often the heater went on in the SFIS greenhouse, the red line shows when the heater was on. From many graphs similar to this, it was estimated that the heater runs for about 30 percent of the day and 50 percent of the night. At the Tesuque

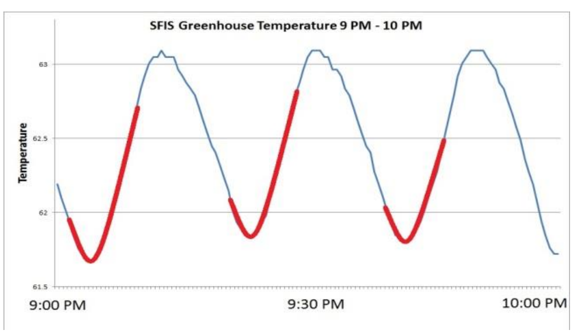

Figure 4: Heater Usage in SFIS

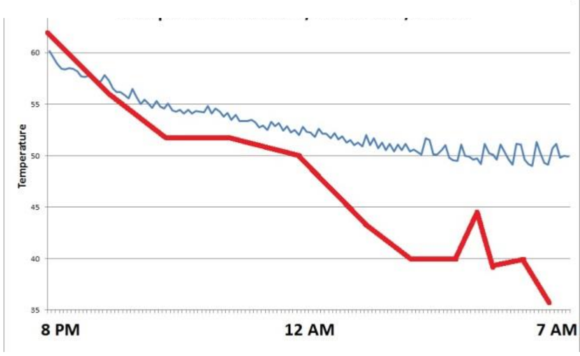

Figure 5: Heater Usage in Tesuque

greenhouse, we saw similar heater usage; however the heater failed to even keep the greenhouse temperature to the thermostat setting of 60 degrees Fahrenheit. There is very little insulation in these greenhouses so temperature is not maintained inside unless heaters and coolers are used.

The second objective was accomplished by first researching retrofits that are currently in use in greenhouses around the country, as well as other theoretical practices that could potentially be useful. The team eventually narrowed down a list of possible retrofits to a mudroom, a 2-foot insulating knee wall around the inside perimeter, a fully-insulated north wall, a retractable energy curtain, and a permanent translucent insulating cover for the roof, such as a layer of bubble wrap. The team tested these ideas using two different methods. First, the team built a 12 by 20 foot experimental hoop house that we used to tested several retrofits, including a bubble wrap coated roof and an insulating knee wall. For the retrofits that were too expensive and time consuming, we used a USDA program called Virtual Grower 3.0 to theoretically estimate the effects.

Figure 6: Hoop House with Bubble Wrap and Insulation

As there is increased interest in the creation of efficient and sustainable greenhouses, this led us to our third objective. Through extensive research and the help from several experts on the subject we produced a set of guidelines to build a sustainable greenhouse appropriate to the Santa Fe, New Mexico area. Our design uses a minimal amount of glazing materials, has highly insulated walls, and couples the greenhouse to the earth, using below-ground insulation to add thermal mass. These design characteristics led to a sustainable greenhouse that can be operated at very low cost using only a small amount of energy. Additionally, we propose that adobe be used to build the insulated walls so that the greenhouse fits in with the culture of Santa Fe. Adobe acts as a great thermal mass and can hold heat in the greenhouse during colder nights. Solar energy is widely available in New Mexico and solar panels should be used to power any mechanical processes such as automated shutters.

For our last objective our project team has left behind several educational resources including an educational website, a greenhouse construction video, and an interactive guide on greenhouse techniques. The educational website includes information on how to build your own greenhouse, different tools to measure efficiencies, how to choose the right glazing material, current sustainable practices around the world, and general information on the need for greenhouse farming and sustainability. The educational video shows the team building a greenhouse and is narrated with advice on how to make a greenhouse more sustainable. Lastly, the guide provides an easy and quick way for people to become more familiar with greenhouse efficiency, with regards to energy use, water consumption, design, and orientation. With the implementation of all of our objectives, we created essential tools for efficiently sustaining the indigenous crops of Northern New Mexico.

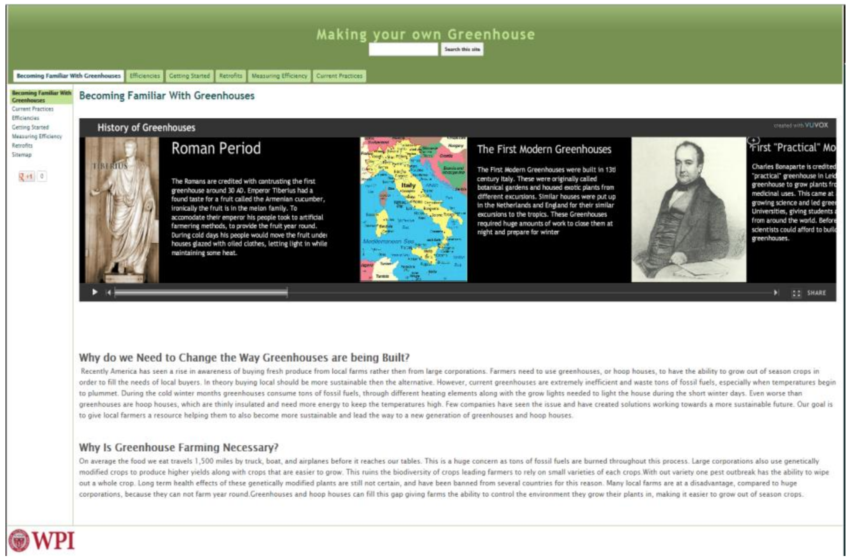

Figure 7: Home Page of Educational Website

Authorship

Section	Contributing Authors	Reviewers
1 Introduction	Basehore, Kiely, Taber, Whitcher	Basehore, Kiely, Taber, Whitcher
2 Background	Basehore	Basehore, Kiely
2.1	Whitcher, Kiely	Kiely, Whitcher
2.2	Basehore	Basehore, Kiely
2.3	Taber	Kiely, Taber
2.4	Basehore	Basehore, Kiely
2.5	Whitcher	Kiely, Whitcher
3 Methodology	Taber	Kiely, Taber
3.1	Taber	Kiely, Taber
3.2	Kiely	Kiely
3.3	Kiely	Kiely
3.4	Basehore , Taber, Whitcher	Basehore, Kiely, Taber, Whitcher
4 Results and Analysis	Taber	Basehore
4.1	Basehore	Whitcher
4.2	Whitcher	Basehore
4.3	Taber	Kiely
5 Conclusions and Recommendations	Whitcher	Kiely
5.1	Basehore	Taber
5.2	Basehore	Taber
5.3	Kiely	Whitcher

Contents

List of Figures

List of Tables

1 Introduction

Greenhouses have been used since Roman times to control the environments that crops grow in.[1] Greenhouses provide a suitable environment for the intensive production of various crops. They are designed to provide control as well as to maintain solar radiation, temperature, humidity and carbon dioxide levels in the aerial environment.[2] This allows farmers to extend the growing season and make it possible to grow crops in more varied climates. In the past 100 years the world's climate has been unpredictable and the need for farmers to control the climates their crops grow in has increased. The United Nations Intergovernmental Panel on Climate Change has reported that 11 of the last 12 years have been the warmest since the 1850's. With increases in temperature, droughts have become more prevalent around the world making it even more difficult for farmers to reliably grow their crops.

A 2010 study concluded that 22% of the world's plant species should be classified as "threatened," as they are at risk of extinction largely due to reduced habitats and climate change as a result of global warming.[3] "Agrifarm" companies, such as Monsanto, have tried to combat this climate change by genetically modifying their seeds to withstand harsher climates. However, crops can only be made resistant to a certain degree so genetic modification cannot be the complete answer. Additionally, these "agrifarm" companies have used patents and "Terminator Technology" to dominate agricultural societies around the world. Not only do the patents mean that single companies can control the production of a given kind of genetically-modified crop, but the "Terminator Technology" allows these companies to make the plants unable to reproduce, thereby compelling farmers to continue to buy their seeds year after year. Finally, people wishing to preserve certain crops may not wish to do so by genetically-modifying them, especially if the crops are an important part of a culture. Therefore, many people are interested in the alternative method of dealing with climate change: making the climates that the crops grow in less harsh. Farmers have been doing exactly this using greenhouses and hoop houses. The maximum crop response depends on the level of the balanced environmental parameters. Off seasonal cultivation is quite possible in greenhouses and it improves economic conditions for farmers.[4]

On a local scale, the climate change has drastically affected agriculture in Santa Fe, NM. There has been a trend of delayed winter onset, which affects the snowfall. This decreases the amount of surface water available for irrigation and farming. Additionally, the delayed winter shortens the farming season greatly. This does not allow the natives to farm traditionally. Understanding the relationships between indigenous people and their threatened economic plants can aid the conservation effort on many

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[1] Taft, L. R.. *Greenhouse construction a complete manual on the building, heating, ventilating and arrangement of greenhouses, and the construction of hotbeds, frames and plant pits*. New York: Orange Judd Company, 1893.
[2] Panwar, N. L., S. C. Kaushik, and S. Kothari. "Solar greenhouse an option for renewable and sustainable farming."*Renewable & Sustainable Energy Reviews*15, no. 8 (2011): 3934-3945.
[3] Shukman, David. "BBC News - One-fifth of world's plants at risk of extinction." BBC - Homepage. http://www.bbc.co.uk/news/science-environment-11434109.
[4] Panwar, N. L., S. C. Kaushik, and S. Kothari.

levels.[5] The natives in Santa Fe hope to preserve crops that are important to them, without the use of scientific modification. One of Monsanto's branches is located in New Mexico; however, if the locals used the company's seeds, it would alter the biodiversity of crops. The natives want to use sustainable greenhouse technology to expand their farming season as a way to restore their income and maintain their cultural traditions. The existing greenhouse in Tesuque Pueblo has 1100 square feet of space and can hold 60,000 seedlings, which they transport to their field in the early spring. The greenhouse uses more energy than necessary to operate and costs more to operate than it could as well. This is also true for the greenhouse at the Santa Fe Indian School. The sponsors have not tried to improve the efficiencies of their greenhouses or to reduce costs recently, so there are still many ways to update them with modern technology to make them more efficient and sustainable.

For our project we will try to help the Tesuque and Santa Fe Indian School fill these inefficiency gaps. To do this we will measure the current efficiency of our sponsors' greenhouses by using methods such as a thermostat that can sense changes in the internal climate of the greenhouse and automatically activate proper functions could improve the energy efficiency. We will then research possible ways improvements to the current designs such as a drip irrigation system to reduce water waste, insulating shutters that could be closed at night to keep the greenhouse warm, and either placing plants on shelves or hanging them from the roof to make more efficient use of the limited space. The selection of the most appropriate technique for both new and existing greenhouses is a challenge for many greenhouse managers who seek to operate profitable businesses in a market that currently provides only moderate financial returns.[6] Finally, we will analyze what we find to determine the improvements that are most needed for our sponsors' greenhouses.

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[5] Burgess, M. A. "Cultural responsibility in the preservation of local economic plant resources." *Biodiversity and Conservation*3, no. 2 (1994): 126-136.

[6] Connellan, G. J.. "Selection of greenhouse design and technology options for high temperature regions."*International Symposium on Design and Environmental Control of Tropical and Subtropical Greenhouses* 1 (2001): 113-117.

2 Background

In a period in which weather patterns have become almost impossible to predict it has become more important that farmers have a way to control the climate their crops are growing in. One way to combat this is to genetically modify seeds that will withstand harsher climates. However, this brings to light the issue of ruining biodiversity of certain plants. Huge corporations are already taking advantage of this new science genetically modifying seeds in mass numbers, making local farmers dependent on their seeds. A second way to fight the climate changes is for farmers to control the climate their plants grow in, by building a greenhouse.

There are many factors that need to be considered when constructing a greenhouse. Such factors include orientation, structure, ventilation, insulation, materials, energy source, and cost. Overall, the total efficiency of the greenhouse is the most important factor. The main goal is to create a sustainable greenhouse. To do this, the most efficient technology and practices must be determined and implemented.

2.1 Growing Need for Greenhouse Farming

The concept of greenhouse farming has existed for thousands of years, dating back to the Roman Empire, where Emperor Tiberius ate cucumbers every day all year round.[7] According to most accounts, the Roman farmers were able to extend the growing season by using manure and hot water in bronze pipes to keep the soil warm and grow the plants in pits.[8] The most basic reason why people built greenhouses was to extend the growing season and to change the environment so that exotic plants could be grown in habitats to which they are not native. Today, farmers still build greenhouses for this very reason: to provide improved climate conditions that are more suitable for the needs of their crops.

2.1.1 Global Climate Change

Greenhouses are becoming more prevalent due to the changes in the climate. With the rising global temperatures, it is becoming more difficult for farmers to complete a growing season without losses due to excessive heat or crops dying as a result of dehydration in the summer months. With more erratic seasons occurring with altering climates, growing seasons have suffered somewhat, becoming shorter some years, not allowing farmers enough time to grow for the full season. Climate change is clearly an issue that farmers are trying to combat. While greenhouses are certainly a necessary part of the solution due to the fact that they provide an alternate environment for crops to grow in, there are a few reasons why the main alternative solution—modifying crops to make them resistant to harsher climates—often has undesirable consequences.[9]

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[7] Nelson, Jennifer Schultz. "Cucumbers - Plant Palette - University of Illinois Extension serving Dewitt, Macon and Piatt Counties." University of Illinois Extension - University of Illinois at Urbana-Champaign. http://web.extension.illinois.edu/dmp/palet.

[8] Taft, L. R.. *Greenhouse construction a complete manual on the building, heating, ventilating and arrangement of greenhouses, and the construction of hotbeds, frames and plant pits*. New York: Orange Judd Company, 1893.

[9] Ahmed, Iqbal. "KILLER SEEDS: The Devastating Impacts of Monsanto's Genetically Modified Seeds in India | Global Research." Global Research: Center for Research on Globalization. http://www.globalresearch.ca/killer-seeds-the-devastating-impacts-of-monsanto-s-genetically-modified-seeds-in-india/28629.

2.1.2 Effects of Sterile Seed Technology and Patents

An increasingly common way to modify crops to make them more resistant to harsher climate conditions is to genetically-modify them. Companies like Monsanto have created seeds that can continue to grow through droughts, grow significantly faster than traditional seeds, and grow in extreme hot or cold conditions. For farmers that are massive produce suppliers, these seeds can be rather beneficial, because the farmers are able to grow large numbers of crops without having to worry about droughts or heat as much as usual. However, with new technologies to make genetically-modified weather-resistant crops have come other technologies and practices that result in undesirable consequences.

For example, Sterile Seed Technology, which allows companies like Monsanto to make their seeds last for only one generation, essentially forces farmers to continue to buy seeds from them year after year if they want to continue using the same kind of weather-resistant seeds. Farmers have typically used seeds from previous seasons for future harvests, this new need to buy new seeds every year, especially from the same company, has been unpopular.

However, even without the problem of Sterile Seed Technology, patent law has allowed companies like Monsanto to grow very large and harass many farmers. Between 1997 and April 2010, "Monsanto filed 144 patent-infringement lawsuits against farmers… and won judgments against farmers it said made use of its seed without paying required royalties."[10] The farmers say that that their fields were contaminated with Monsanto's genetically-modified patented seeds without their knowledge, but Monsanto has still won several cases and farmers have been forced to pay.[11]

Additionally, some of Monsanto's genetically-modified seeds are actually toxic to many organic crops. Monsanto has endured multiple lawsuits from small farmers regarding devastating losses to the farmers' crops because winds have carried Monsanto seeds onto their land and killed their organic crops.

Although seeds that are genetically-modified to be resistant to harsher climates can be useful to some farmers, most traditional farmers are adamantly against the practice of genetically-modifying seeds and the companies that engage in this practice such as Monsanto. They are opposed to companies like Monsanto because they produce and promote Sterile Seed Technology, or "Terminator Technology," seeds. These companies control the market and abuse their power. Further, for farmers wishing to preserve traditional crops, genetically-modifying them does not appear to be an attractive solution.

Locally, many native New Mexico farmers have struggled against the presence of Monsanto and other companies that produce genetically-modified seeds. In order to help combat their presence, some of these small farmers have developed seed banks to protect their seeds and then plant them the following season. Additionally, more farmers are looking to change the climates that their crops grow in to suit their needs rather than modify their crops to make them resistant to more diverse climates. This is accomplished using greenhouses.

[10] Gillam, Carey. "Monsanto Lawsuit: Organic Farmers Appeal U.S. District Court Decision." Breaking News and Opinion on The Huffington Post. http://www.huffingtonpost.com/2012/03/28/monsanto-lawsuit-organic-farmers-appeal_n_1385693.html.

[11] *Ibid.*

2.1.3 Climate Diversity in New Mexico

New Mexico has one of the most diverse climates in the United States. Because of its high elevation, there is a tremendous temperature swing throughout the day. During the spring in New Mexico, it is not uncommon for the temperature to be over 80°F during the day and below 30°F after the sun sets. Additionally, the varied elevations throughout the state cause multiple climate pockets. In the northern regions of New Mexico, the elevation is significantly higher than most other parts of the state, which cause much more significant temperature fluctuations, but there is also more precipitation in that area than others. For the southern and eastern regions of New Mexico, rain is more of a rarity than in the north, so those regions rely on the monsoon months of July and August to provide most of their water for the year. Specifically in the Tesuque Pueblo, located in northern New Mexico, the growing season is nearly a month shorter than many other regions surrounding it because of the temperature changes. With such a diverse climate, farmers in New Mexico have very realistic needs to be able to control their environment and extend their growing season as much as they can, which is why the use of a greenhouse would be highly beneficial to the region.

Figure 8: Map of New Mexico Climate Diversity

2.2 Overview of Greenhouses

The Romans were the first society to develop a loosely controlled environment in order to grow out of season crops around 30 AD. Roman Emperor Tiberius had a fond taste for the Armenian Cucumber, to accommodate their emperor his people took to artificial farming methods. The Roman people built a crude greenhouse moving the Armenian Cucumber under oiled clothes, allowing light to pass through while still retaining some heart[12]. However 13th century Italians are credited with building the first modern greenhouses, originally called botanical gardens. Italy along with the Netherlands and England had returned from excursions to the tropics and returned with many exotic plants that could

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12 "The History of Greenhouses." Greenhouse Gardening. As Easy as 1-2-3!! . http://www.123-greenhouse-gardening.com/history-of-greenhouses.html (accessed April 18, 2013).

not survive in their own climates[13]. The only solution for these countries was to build controlled environments where these new tropical plants could be grown in. In the Following Centuries botany grew as a science and leading universities began to build greenhouses, students could now study plants from all around the world[14]. Greenhouses have evolved with technology; the inventions of glass and then plastics have led to many different styles of greenhouses. However, one aspect that has remained constant is the reason for greenhouses. Throughout time civilization has had a need to control the environment in order to produce diverse crops. Currently there are roughly three different design types including:

- Hoophouses/Passive Greenhouses
- Active Greenhouses
- Sustainable Greenhouses

2.2.1 Hoop Houses/Passive Greenhouses

By definitions a passive greenhouse is a greenhouse that does not utilize any outside heating source aside from the sun[15]. Instead these houses use the sun and materials with high specific heat values, such as water or concrete. These materials then heat the greenhouse by radiating heat back into the greenhouse while the sun goes down. A common type of passive greenhouse is the hoop house, which is an inexpensive solar structure designed to protect crops from the harsh climates each of the four seasons bring with them. Hoop houses give farmers an inexpensive way to pick and choose what types of crops they want to grow, allowing them to reach the demand of their customers. Author and Farmers Steve Moore hits the essences of a hoop house with his four points[16].

Figure 9: Passive Hoop House

[13] Woods , Mary , and Arete Swartz . "Glass houses. A History of Greenhouses, Orangeries and Conservatories ." In*Garden History* . Edinburgh : The Garden History Society , 1988. 203

[14] Ohio State University . "History of Campus Greenhouses | Biological Sciences Greenhouse." Home | Biological Sciences Greenhouse. http://bioscigreenhouse.osu.edu/about/history-campus-greenhouses (accessed April 18, 2013).

[15] University of Missouri . "Bradford Research and Extension Center: Building a Passive Solar Greenhouse." CAFNR: Agricultural Experiment Station. http://aes.missouri.edu/bradford/education/solar-greenhouse/solar-greenhouse.php (accessed April 18, 2013).

[16] Blomgren, Ted, and Tracy Frisch . "Introduction ." In *High Tunnels*. Burlington : University of Vermont Center for Sustainable Agriculture, 2007. 1.

- Hoop Houses should capture as much energy as possible
- Hoop Houses should conserve as much energy as possible
- Hoop Houses should be simple and mechanically managerially
- Hoop House design should operate for minimal economic risk and quick payback.

2.2.2 Active Greenhouses

In contrast to a passive greenhouse, an active greenhouse seeks alternate ways to heat and cool the structure; they are usually run on a thermostat much like a house. While a passive greenhouse is meant to operate at minimal cost, an active greenhouse is built for high yield production purposes. Active greenhouses generally use unit heaters to keep higher temperatures during the night along with different types of vents and fans to keep the greenhouse cool during hot days. Unfortunately many greenhouses are constructed of only polyethylene, glass, or polycarbonates, all of which have extremely low R-values (higher r-value = better insulator). Greenhouses are poor insulators causing heaters and- fans to run constantly, this leads to high-energy usage. This high use of energy allows for active greenhouses to run all year; however they are costly and extremely inefficient[17].

Figure 10: Active Greenhouse with Heater

2.2.3 Sustainable Greenhouses

Recently several groups have seen a need for a more sustainable and energy efficient greenhouse, requiring minimal energy use but high production yields. These sustainable greenhouses utilize low energy costs with sustainable building practices, such as using less energy intensive materials. An ideal greenhouse is one that can grow food year round, however, can also be passive and use mostly solar energy. Larry Kinney president of Synergistic Building Technologies suggests four major principles when developing a sustainable greenhouse[18]

Figure 11: Sustainable Greenhouse

[17] Manohar , Radha , and Igatidnathane C. .*Greenhouse Technology and Management*. 2nd ed. Global Media : Global Media , 2007

[18] Kinney, Larry . "Energy Efficient Greenhouse Breakthrough ." *Summer Study on Energy Efficiency in Buildings* 1, no. 1 (2012): 3-4.

- Keep the time constant of the building long through insulation and thermal mass
- Control the flow of the solar flux, both light and heat
- Control the temperature and flow of the air
- Integrate the systems of the greenhouse to optimize plant growth

2.3 Sustainable Greenhouse Design Considerations

When constructing a greenhouse the builder must take many things into consideration in order to make the house as sustainable as possible. Things to take into consideration include how to heat the greenhouse, how to orient it, what watering system to use, and what the glazing materials should be used. Through the team's research, it is evident that there are four major efficiencies to look at during construction:

- Site
- Glazing
- Water
- Energy

2.3.1 Site Efficiency

The first factor to look at when designing and constructing a greenhouse is figuring out the best location and orientation of the building. Orientation determines how much solar heat the greenhouse will absorb during the day and an appropriate structure will retain the maximum amount of heat. This will extremely aid in the overall efficiency of the greenhouse.

Orientation of Greenhouse

The efficiency of the greenhouse structure is determined by its ability to store the heat of the solar radiation energy. The determining energy characteristics of the solar greenhouses are as follows: maximal solar radiation input to the greenhouse; minimal heat losses; maximal storage of the heat of the solar radiation energy entering the greenhouse.[19] Therefore, it must be oriented in a way that allows maximum penetration of sunlight. Solar greenhouses are relatively inexpensive and easy to build.[20] According to the Solar Greenhouse Book, "solar radiation is the driving force of the greenhouse; it supplies not only the light necessary for plant growth, but also the heat necessary to maintain a growing environment."[21] Solar energy is measured in Btu's (British thermal units) per square foot per hour. A BTU

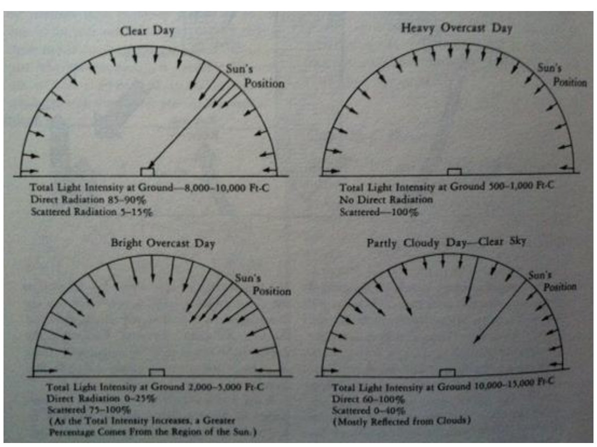

Figure 12: Sky Dome and Radiation

[19] Khalimov, A. G., B. E. Khairiddinov, and V. D. Kim. "Raising the efficiency of solar greenhouses." *Applied Solar Energy* 44, no. 3 (2008): 166-168.

[20] Conservation and Renewable Energy Inquiry and Referral Service, S. S. M. D. "Build a Solar Greenhouse." (1984).

[21] McCullagh, James C. *The Solar greenhouse book*. Emmaus, PA: Rodale Press, 1978.

is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. The maximum intensity of sunlight, at 40 degrees North latitude, is 306 Btu per square foot per hour. In the winter, the intensity of direct solar radiation is about 290 Btu's per square foot per hour at noon (40 degrees north latitude). At this intensity, the solar energy is strong enough to pass through a 12' by 16' greenhouse in one hour to heat the inside from 40 degrees to 70 degrees. During the hottest seasons where the solar energy is greater than 290 Btu's per square foot per hour, a solar greenhouse would experience an even greater heat change to maintain the inside climate needed to grow crops and plants.[22] The intensity of the sunlight is also affected by overcast and partly cloudy days. The figure below depicts the sky dome and the amount of direct solar radiation on the ground depending on the type of weather.

On a clear day, the direct radiation is 85-90% whereas on a heavy overcast day, the direct radiation is 0%. Partly cloudy days are the hardest to quantify because white clouds reflect the solar radiation on the greenhouse as well, thus increasing the direct radiation. Therefore, the intensity of sunlight can vary depending on the amount of clouds in the sky and the intensity of the sunlight throughout seasons.[23]

The orientation of the windows on the greenhouse can significantly change the amount of solar energy produced as well. The solar greenhouse book discusses the difference of direct solar radiation depending on the orientation of the glazing wall which collects the sunlight.

The figure shows that a greenhouse receives the most radiation when the glazing wall faces true south. The other end of the greenhouse can be opaque and insulated to aid decrease in heat loss and radiation loss. When the greenhouse glazing wall is oriented 20 degrees from true south, either facing east or west, about 4-5% of direct radiation is lost. When the greenhouse glazing wall is oriented 45 degrees from true south, 18-22% of direct radiation is lost. Therefore, the greenhouse should ideally be facing true south to maximize solar radiation.[24]

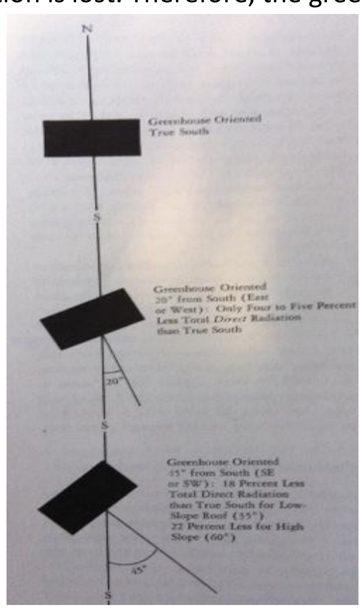

Figure 13: Orientation Effects on Radiation

[22] *Ibid.*
[23] *Ibid.*
[24] *Ibid.*

Shape of Greenhouse

The style and shape of the greenhouse is not the only important aspect to consider; the materials are important too as the selected materials must be compatible with the structure style for a greenhouse to be successful. A study called "On the selection of shape and orientation of a greenhouse: Thermal modeling and experimental validation" compared the five most commonly used single span shapes of greenhouses. The five shapes, shown below, are even-span, uneven-span, vinery, modified arch and quonset type. The length, width and height (at the center) were kept same for all the selected shapes to help with comparisons. Using a mathematical model, the total transmitted solar radiation at each hour, for each month and at any latitude for the selected geometry greenhouses (through each wall, inclined surfaces and roofs) were developed for both east-west and north-south orientations. During the experimentation, capsicum crop was grown inside the greenhouse.[25] The best shape of the greenhouse was determined after all calculations and comparisons were found.

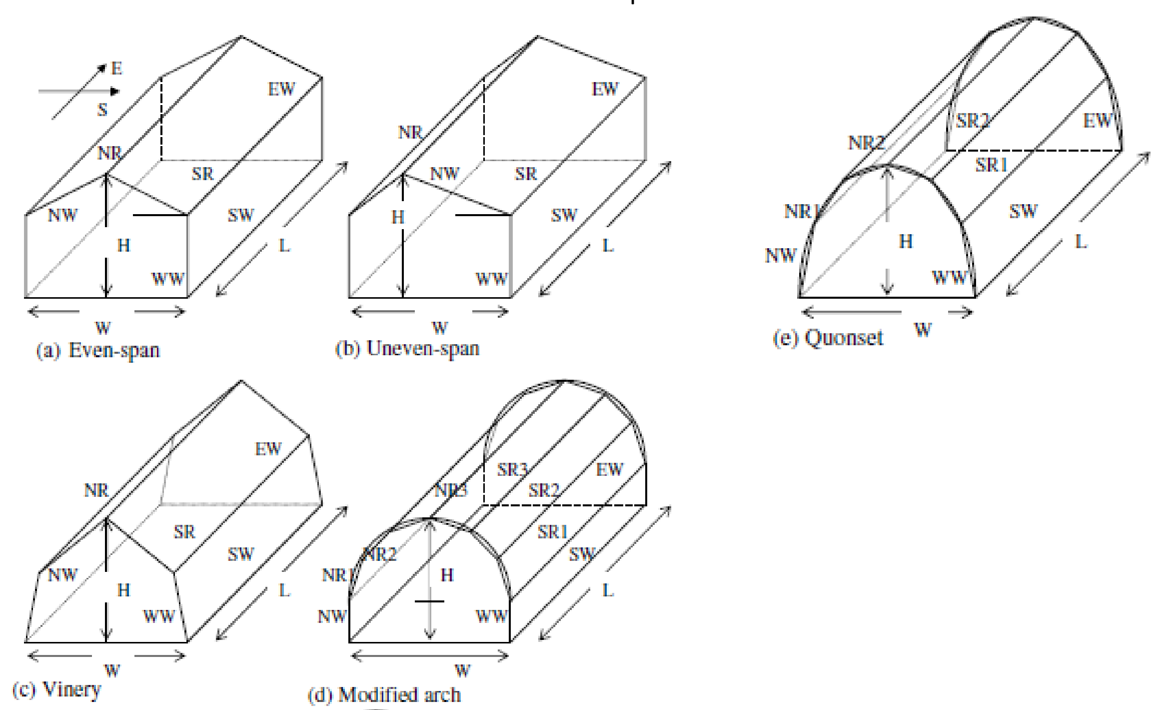

Figure 14: Shapes of Greenhouses

In general, a greenhouse receives most of the beam radiation at its floor, which is responsible for the increase in inside air temperature. Apart from this, greenhouse also receives diffuse and ground

[25] Sethi, V. P. "On the selection of shape and orientation of a greenhouse: Thermal modeling and experimental validation."*Solar Energy* 83, no. 1 (2009): 21-38.

reflected radiation from each wall and roof, thus shape and orientation of the greenhouse also has some bearing on the greenhouse air temperature which further affects the inside temperature. The selection of optimum shape and orientation of a greenhouse can lower the heating and cooling loads of the installed systems thereby saving a lot of operating cost. Figure 14 above shows the different shapes and the differences in layout of the shapes.[26]

Although the length, width and height for all the greenhouse shapes is the same (6 m, 4 m and 3 m, respectively), due to the difference in the ratio of the cover to the floor area (Ac/Ag) of each shape, the total amount of solar radiation received from the whole greenhouse would automatically be different for each shape. The following graph demonstrates the total yearly amount of solar radiation available at different latitudes (10, 31, and 50) in orientation for each of the five shapes.[27]

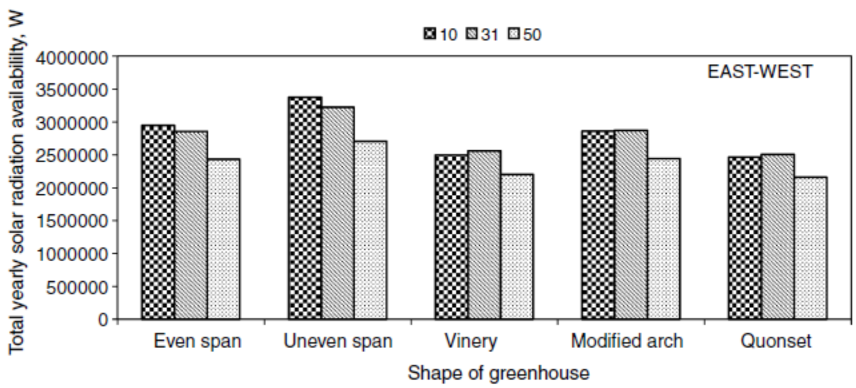

Figure 15: Total Solar Radiation Available at Different E/W Latitudes

As shown, the highest amount of solar radiation occurs at 10 degree latitude and the best shape is the uneven span shape. Another factor to consider is the amount of solar radiation during the summer verse the winter months. Since the ideal goal of the greenhouse is to be able to grow crops during the winter months, it is essential to know the amount of solar radiation available during these months to ensure that the inside can maintain normal climate for plant growth.[28]

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[26] *Ibid.*
[27] *Ibid.*
[28] *Ibid.*

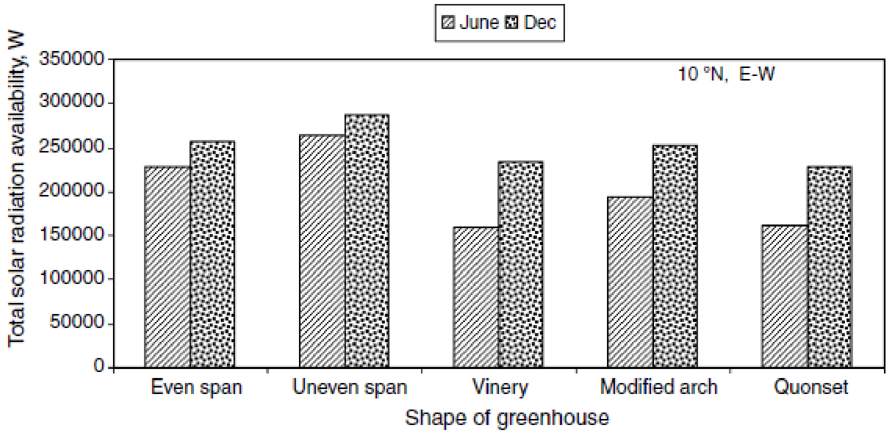

Figure 16: Total Solar Radiation Available in Winter and Summer at 10 Degrees N

At 10 degrees N latitude, in June, an uneven-span shape receives 15.8% more radiation as compared to even-span shape as seen in Figure 16. Modified arch shape receives 15.2% less radiation, whereas vinery and quonset shapes receive 30.5% and 29.2% less radiation as compared to an even-span shape. Similarly, in December, an uneven-span shape receives 11.8% more radiation as compared to an evenspan shape. Modified arch shape receives only 1.2% less radiation, whereas vinery and quonset shapes receive 8.8% and 10.8% less radiation as compared to even-span shape. It can be concluded that a greenhouse shape which receives minimum solar radiation would be most suitable. From this study specifically discussing the amount of solar radiation available, the uneven span shape is ideal.[29]

The next focus point is the temperature inside the greenhouse throughout the day amongst the five different shapes. For this study, the greenhouse air temperature (TR) during each hour for each selected shape (both E-W and N-S orientation) was computed using mathematical equations.

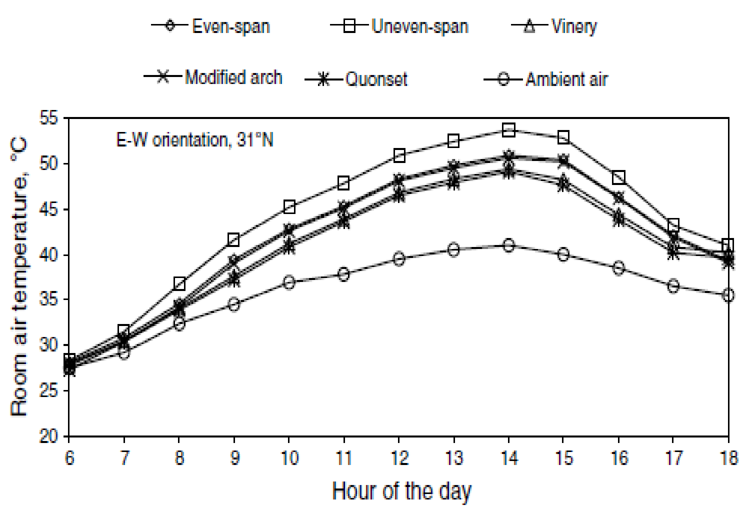

Figure 17: Hourly air temperature (during sunshine hours) for different shapes at 31 Degrees Latitude

The maximum rise with respect to ambient air temperature is 12.7°C with average rise during the whole day is 8°C. Maximum rise in TR for the even-span shape is 9.9°C with average rise during the

[29] *Ibid.*

whole day is 6°C. Maximum rise in TR for the modified arch shape is 9.4°C with average rise during the whole day is 5.8 °C. Maximum rise in TR for the vinery shape is 8.3°C with average rise during the whole day is 4.9°C. Maximum rise in TR for the quonset shape is 8.1°C with average rise during the whole day is 4.5°C. It is clear that inside air temperature rise depends upon the shape of the greenhouse. It can be observed that TR remains significantly higher for an uneven-span shape as compared to ambient air temperature (for all hours).[30]

From this study, it can be seen that the pattern and amount of solar radiation availability at different latitudes is different for the same greenhouse shape. An uneven-span shape greenhouse receives the maximum solar radiation during each month of the year at all latitudes, whereas quonset shape receives the minimum solar radiation during each month of the year at all latitudes. At 10°N latitude, all the selected shapes receive more radiation in winter but less in summer. Whereas at 31°N, the same greenhouse shapes receive less amount of solar radiation in winter months but greater in summer months. Finally, the air temperature remains the highest inside an uneven-span shape and the lowest in a quonset shape as compared to other shapes during different months of the year.[31] All in all, it can be concluded that the uneven-span shape is the best shape for a solar greenhouse. A structural shape that aids the solar radiation will be most efficient for energy and cost. When solar radiation is the key energy source, money will be saved since the greenhouse will not rely on electricity.

2.3.2 Glazing Material Efficiency

Greenhouses are required to have high light transmission, adequate structural strength, and low cost of construction.[32] Choosing a material that will cover your greenhouse or hoop house, known as the glazing material, is an integral part of the building process. Traditionally people have used glass, in signal and double panes, however recently new plastics have been introduced to greenhouses and hoop houses. When choosing a glazing material there are many different aspects to look at; for example glass allows direct sunlight in the greenhouse while different plastics diffuse sunlight. Both direct and diffused sunlight have their advantages; plants grow best when given direct sunlight, however, direct sunlight creates shadows in the greenhouse, causing uneven plant growth. On the other hand diffused light gets spreads evenly within the greenhouse; therefore all plants get a uniformly distributed amount of light. Many other factors play a role when choosing a glazing material such as:

- Lifespan
- Resistance to hail and rocks
- Ability to support snow
- Resistance to Condensation
- Amount of support needed to hold up material
- Fire Resistance
- Ease of installation
- Cost efficiency

[30] *Ibid.*
[31] *Ibid.*
[32] Bailey, B. J, and G. M Richardson. "A Rational Approach to Greenhouse Design." *Acta Hort. (ISHS)* 281, no. 1 (1990): 111-118.

- R-value/ U-value (measure of insulation)

Glass

Historically glass has been the “go to” material when building a greenhouse, mainly because it is the oldest of all glazing materials. A huge advantage of using glass is it lifespan is indefinite, unless broken. Glass allows an upwards of 90 percent light transmission, making it the best of all glazing materials.[33] However glass is fragile, making it easy to break and requires many support beams to prevent the glass from snapping. Fortunately tempered glass has been introduced making the glass stronger, needing less support; however this comes with a price increase. Glass also does not diffuse light, causing uneven growth of the plants within the greenhouse. Lastly, single pane glass is not very insulating requiring structures to use two layers. The double pane style greatly increases the insulation, making it more efficient than any other material. However the double pane glass is very heavy making installation difficult as well as reduces the amount of light transmitted through the glass.

Plastic

Polyethylene and polycarbonate are the two most commonly used glazing materials, aside from glass. Polyethylene has similar characteristics to glass when it comes to light transmission and insulation. However, polyethylene is more cost efficient and easier to install. Different treatments can be applied to Polyethylene in order to make the material resistant to condensation along with cracking or tearing in the cold temperatures. Double layers of polyethylene are often used to lower the heat loss within the greenhouse. However this plastic has several huge downfalls that some builders cannot overlook. The material is not tough and can easily tear, even after treatment. Polyethylene also has a short lifespan, UV-resistant polyethylene only last a maximum of 2 years. The light transmissions also decrease over time, making the material less efficient shortly after construction. A study done in Saudi Arabia showed that the mechanical resistance of polyethylene was reduced when exposed to an arid climate similar to that of Santa Fe.[34] Finally, the material is inconsistent with the temperature, expanding in warmer weather and shrinking in colder weather, this needed to be accounted for in the building of the greenhouse.[35]

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[33] Bellows, Barbara. " Solar Greenhouse Resources." National Sustainable Agriculture Information Service. http://www.agrisk.umn.edu/cache/arl01480.htm.
[34] Alhamdan, A. M, and I. M Al-Helal. "Mechanical deterioration of polyethylene greenhouses covering under arid conditions." *Journal of Materials Processing Tech* 209, no. 1 (2009): 63-69.
[35] Bellows, Barbara.

Material	Life Expectancy (years)	Light Transmission (%)	Heat Transfer Coefficient (U Value, Btu/hr/ft²/°F)
Glass	30+	90	1.1
Polyethylene (single layer)	4	88	1.1
Polyethylene (double layer)	4	77	0.7
Polycarbonate	10	75	0.6

Table 1: Glazing Material Efficiency Table

Polycarbonate is similar to glass and polyethylene having a relatively high light transmission. However, it is 1/6 the weight of glass and is still superior to both glass and polyethylene in the area of insulations when applied in single layers.[36] This plastic usually comes in a minimum of a double layer and often three or four layers. Without treatment polycarbonate is resistant to UV light and highly resistant to fire. Even though polycarbonate is very lightweight it is also very strong, and can therefore withstand things such as heavy snow loads. Polycarbonates shelf life is not indefinite, however it last to an upwards of ten years and is easily installed. The downfall of the plastic is that it is more expensive than most plastics and it is not translucent, therefore natural light is scarce within the greenhouse.[37]

2.3.3 Water Efficiency

Climate-change projections warn us to expect more extreme weather conditions, including both more frequent and more severe flooding and droughts. When it comes to dry conditions, one way to reduce the pressure on stressed public water supplies and wetland habitats is to save rainwater using a collection system.[38] In New Mexico, the climate change has affected the rainfall. In fact, the area is currently in a state of drought. Therefore, water retention is extremely important. There are many systems of rainwater collection and moisture reclamation used worldwide. The placement of rainwater collection systems can ideally improve the outlook for locations where water is scarce. This water collection can be used for local farming, especially in greenhouses. Therefore, crops can still be grown and produced year round even in times of drought.

Rainwater Collection

A system that collects rain water is a method for watering the plants that allows the gardener or farmer to use water that saves money, thus increasing the overall efficiency of the greenhouse. At the Santa Fe Indian School and Tesuque Pueblo, inexpensive water sources are scarce and a water collection

[36] "Twinwall and Triplewall Polycarbonate Sheets, Polycoolite, Spring and Lexan Thermoclear Solar Control from Advance Greenhouses." Greenhouses For Sale | Greenhouse Kits | Hobby Greenhouse Accessories and Supplies. http://www.advancegreenhouses.com/twinwall_and_triplewall_polycarb.htm.

[37] Bellows, Barbara. " Solar Greenhouse Resources." National Sustainable Agriculture Information Service. http://www.agrisk.umn.edu/cache/arl01480.htm

[38] Tony, J. "Greenhouse effects: Rain collection." *Sunday Times, NI Syndicated Limited* (London, UK), January 1, 2009.

system is an option that the farm managers wish to explore more. The figure depicts a typical rainwater collection system.[39]

A gutter collection system on the sides of the greenhouse could be used to filter any run-off water from the roof of the greenhouse into barrels or collection points inside or just outside the greenhouse. The water in these barrels will be used to water the plantings throughout the year. Additionally, snowfall in the winter can be collected and melted into water to make up for the lack of rain in the time of drought.[40]

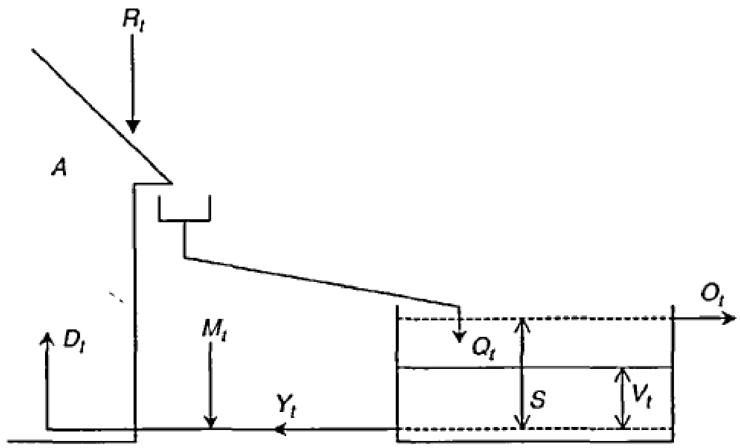

Figure 18: Rainwater Collection System

The paper, "Method of Modeling the Performance of Rainwater Collection Systems in the United Kingdom," simulates the performance of rainwater collectors from 11 different UK locations. A set of performance curves was produced for each of these locations depicting the efficiency of the storage systems. "A number of problems have been linked to centralized systems of water supply and disposal. These include increasing water demand; resources not located in areas of high demand and increased surface water runoff volumes; and discharge rates due to urban and highway development." Although solutions to these problems have been developing new water supplies and distribution networks, alternative and more sustainable strategies include the use of a decentralized technology such as a gutter collection system.[41] The 11 UK locations are shown in the table. The average annual rainfall is also shown for each of the locations.[42]

[39] Fewkes, A, and P Wam. "Method of modelling the performance of rainwater collection systems in the United Kingdom." *Building Services Engineering Research & Technology* 21, no. 4 (2000): 257-265.
[40] *Ibid.*
[41] *Ibid.*
[42] *Ibid.*

Table 1 Average annual rainfall levels of sites

Site	Average annual rainfall (mm per annum)
Cromer	581
Dumfries	1072
Eastbourne	786
Glynllif (Caernarfon)	1124
Goonhaven (Newquay)	1021
Jesmond (Newcastle)	756
Bredenbury	750
Landue (Launceston)	1097
Nottingham	622
Spaxton (Taunton)	859
Weaste (Manchester)	837

Table 2: UK Location and Average Rainfall

The performance of a rainwater collection system in terms of their water-saving efficiency has been modeled successfully using a behavioral model called the YAS model. The model was used to predict system performance of different combinations of roof area, demand, store volume and rainfall level expressed in terms of the dimensionless ratio, the input ratio (AR/D) and the storage period (S/d} in days. The performance curves for each location were closely grouped together, suggesting that system performance was relatively insensitive to daily fluctuations in rainfall at each site. (Fewes and Wam 2000, 7) The close grouping of the water efficiency curves at each site also suggested that system performance could be represented by a set of average curves, one for each input ratio. An example of one of the curves produced can be seen below.

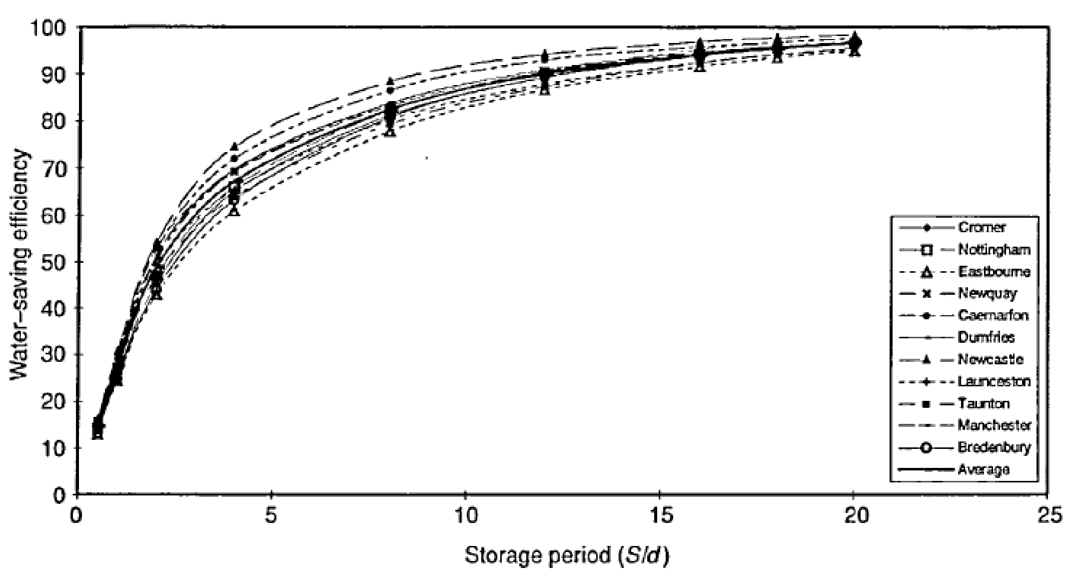

Figure 19: Water Saving Efficiency of a Water Collection System

Figure 19 shows the efficiency of a water collection system at each of the 11 locations in the UK. (Fewes and Wam 2000, 9) The use of a rain water system will make a greenhouse more efficient and sustainable. Therefore, a system such a gutter system should be implemented and utilized by farmers in Santa Fe.

Recycling Water in a Greenhouse

While rainwater collection is one way to make the greenhouse more efficient, wasting water on the inside of the greenhouse will counteract some of the efficiency gained with a collection system. What plants and crops are watered, most of the water is absorbed in the roots; however, some water collects on the floor, on the windows, and other structures inside the building. Depending on the watering system, not all the water that exits the spouts is utilized efficiently. If that water is not recycled back into the system, the water is lost. To make the greenhouse as water efficient as possible, a drainage system on the inside of the building is necessary. If this water is filtered and then pumped back into the collection tank with the rainwater, all the water can be reclaimed and reused.

2.3.4 Energy Efficiency

Energy consumption is a very important factor that contributes to the sustainability of a greenhouse. Ideally, a sustainable greenhouse would be one that is inexpensive to install and maintain, but should have a long lifespan. In a hybrid solar greenhouse having both active and passive solutions are available to increase a greenhouse's energy efficiency.[43] Some topics, such as ventilation, insulation and a useful energy source, emerge as the primary focuses of an energy efficient greenhouse.[44] The main aspects that will account for the energy efficiency of a greenhouse are its ventilation capabilities, how well the greenhouse is insulated, and what it uses as its energy source. Greenhouses that are energy efficient do not necessarily have to function entirely on green energy, as long as the total amount of energy consumed is held to a minimum. This can be accomplished by combining certain aspects of passive technology to substitute for a potentially excessive use of electric power.

Ventilation

In order for greenhouses to maintain their climates, proper ventilation is very useful. Greenhouses use heating fans to circulate warm air through the greenhouse during the colder months and exhaust fans when the weather is warm. Although fans are a very common form of ventilation, greenhouses also use methods such as radiators for heating and simply opening doors and windows for cooling. The image below shows how ceiling fans can be used as active sources of ventilation and to circulate hot or cold air through a greenhouse.

[43] Pierce, B. A. "Water reuse aquaculture systems in two solar greenhouses in Northern Vermont." *Wiley Online Library* 11, no. 1-4 (2009): 118-127.
[44] Baille, A. "Trends in greenhouse technology for improved climate control in mild winter climates." *Acta Hort. (ISHS)*559 (2001): 161-168.

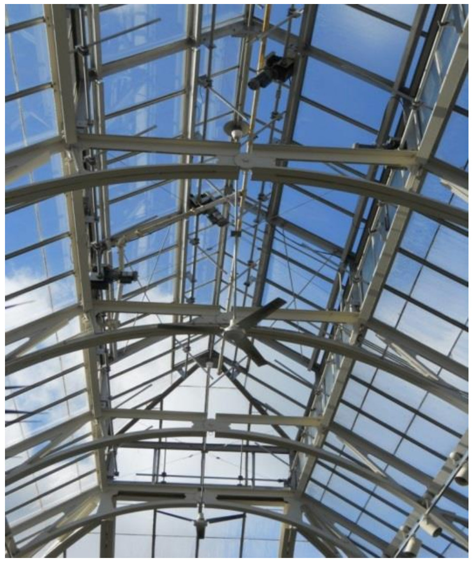

Figure 20: Ceiling fans and motorized vents at Tower Hill Botanic Gardens

Greenhouses are the largest heat energy consumers in agricultural production. Their costs for heat supply can reach 70-80% of the total energy budget.[45] Therefore, newer elements of ventilation are beginning to surface now. The use of passive technology is becoming more widespread and accepted because it requires significantly less power than traditional methods, if it needs any power at all. One example of a passive strategy for energy efficient heating and air circulation is a trombe wall. The way this wall works is that by constructing a south-facing, solar absorbing wall inside the greenhouse with a small airspace between the wall and a glazed surface of the greenhouse, the rays from the sun are absorbed by the dark wall and retained in the airspace. Since hot air is less dense than cold air, it rises to the top of the airspace and is pushed through vents in the wall, circulating the cold air back into the airspace of the trombe wall where it is heated and then rises back up and continues the cycle. Because it functions entirely on natural convection currents, trombe walls have a large appeal to people looking to efficiently heat their buildings.[46] The following diagram depicts the natural convection currents that flow throughout a greenhouse as the solar energy is gathered in the thermal mass then sent through the trombe wall and into the greenhouse.[47]

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[45] Popovska-Vasilevska, S, and K Popovski. "Solar Energy For Greenhouses." (2007).
[46] Alward, Ron, and Andrew M. Shapiro.*Low-cost passive solar greenhouses: a design and construction guide*. 2nd ed. New York: Scribner, 1980.
[47] *Ibid.*

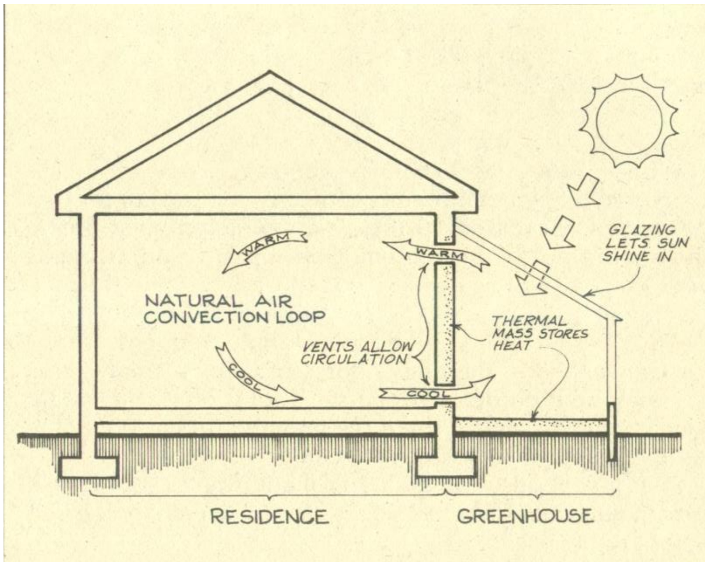

Figure 21: Function of a Trombe Wall

Trombe walls are not the only form of passive energy that can be used in greenhouses though. Modern greenhouses and bioshelters use buried foundations to increase the thermal mass of the structures. The earth's soil retains a large amount of heat when insulated, with soil 30" below the surface potentially being over 10 degrees warmer than on the surface.[48] Although it may not provide as much heat as a trombe wall would, heat exchanger pipes are another very useful option for passive ventilation in a sustainable greenhouse.

Insulation

Farmers can build greenhouses with state-of-the-art ventilation, but without proper insulation, they will not be very energy efficient. As greenhouse technology has evolved, the most noticeable change has been the evolution of its insulation. Beginning from just a pit in the ground, changing to above ground structures shielded by glass, and some greenhouses recently transitioning to plastic panels for windows, greenhouses have undergone substantial changes since their origins. Some new greenhouses are changing shape in order to maximize the amount of sunlight captured and because of this are able to remove some of the windows on the sides of the structure and replace them with insulated siding that people would see in normal houses. As can be seen in this chart matrix, insulation has a direct effect on the cost of energy in a greenhouse. The more money that is spent on thicker insulation, the lower the energy cost is, which will ultimately increase the total payback of the better insulation and translate into more of a profit for the structure.[49]

[48] McCullagh, James C.. *The Solar greenhouse book*. Emmaus, PA: Rodale Press, 1978.

[49] "Maximize System Efficiency with Proper Insulation." U.S. DOE Energy Efficiency and Renewable Energy (EERE) Home Page. http://www1.eere.energy.gov/manufacturing/tech_deployment/winter2009.html.

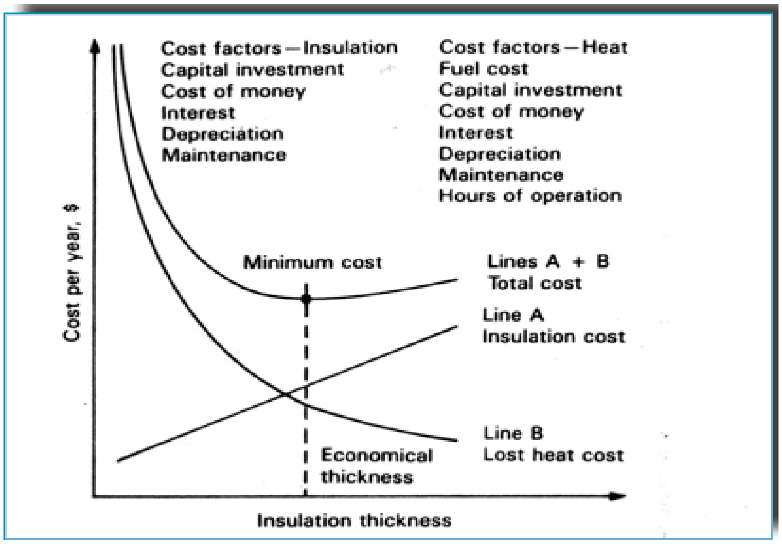

Figure 22: Insulation Cost and Payback Graph

In the 1970's and 1980's, when greenhouses were starting to have a focus more geared toward solar efficiency, the use of insulated shutters became a prominent tool for retaining heat inside the greenhouse. Originally, the glazed surfaces were only insulated by sheets of plywood that the farmers placed over the windows for when the sun set and the greenhouse was beginning to lose heat.[50] The evolution of insulated shutters has developed the use of timers to automatically open and close shutters on the windows and the shutters are made with actual insulation material, further increasing their efficiency.[51]

One kind of insulation farmers can add to their greenhouse is an insulating curtain to put over the roof at night. As much as 80 percent or more of heating energy in greenhouses is used after dark, so a movable insulating curtain can be an effective way to limit nighttime heat lost.[52] There are several different kinds of materials that can be used for the insulating curtain. An important consideration is whether the curtain is to be porous, non-porous, or semi-porous. Non-porous aluminized materials have the advantage of being better insulators—they provide heat retention by up to 70 percent—however they do not allow water to drain through.[53] This can lead to accumulation of the water which can cause the curtain system to fail due to the water's weight. However, in the Santa Fe area in New Mexico this may not be as much as a problem due to the small amount of rainfall relative to many other places in the United States. On the other hand, porous materials do allow water to drain through, but do not insulate as well as non-porous materials. Insulating curtains made of porous materials typically cut heat losses by only about 20 to 30 percent.[54] Semi-porous aluminized materials may be a good middle

[50] McCullagh, James C.. *The Solar greenhouse book*. Emmaus, PA: Rodale Press, 1978.
[51] Kinney, L, J Hutson, M Stiles, and G Clute. "Energy-Efficient Greenhouse Breakthrough." American Council for an Energy-Efficient Economy. www.aceee.org/files/proceedings/2012/data/papers/0193-000414.pdf.
[52] Focus On Energy. "Ten Easy Ways to Cut Energy Costs In Existing Greenhouse Spaces." Michigan State University. hrt.msu.edu/Energy/Notebook/pdf/Sec3/Ten_Easy_Ways_to_Cut_Energy_Costs_In_Existing_Greenhouses_by_WI_Focus_on_Energy.pdf.
[53] *Ibid.*
[54] *Ibid.*

ground. They allow drainage while still cutting heat loss by up to 65 percent.[55] The positioning of the night insulating curtain is also important. In some greenhouses the insulating curtain can just go over the top of the greenhouse, however in some large commercial greenhouses the insulating curtain is placed horizontally within the greenhouse a few feet above the crops.[56] This allows the curtain area to be minimized, thus saving space and reducing the curtain cost. When the curtain is within the greenhouse it is important that the edges of the curtain are closed tightly to prevent warm air from leaking past into the upper section of the greenhouse.

Another kind of insulation that can be used in a greenhouse, especially as a retrofit, is an insulating knee wall going around the perimeter of the greenhouse. “Energy savings can be achieved by insulating side walls, end walls and perimeter with one inch or two inch foam insulation board.”[57] Usually extruded polystyrene Styrofoam insulation is used and it is typically made about two feet tall so that it does not block the sunlight from passing into the greenhouse and reaching the plants.

Alternatively, or in addition to a knee wall, the entire north wall of a greenhouse can be insulated. Due to the fact that the sunlight primarily enters the greenhouse from the south side it is possible to completely cover the north wall of the greenhouse with insulation from floor to ceiling and still have the plants in the greenhouse get the necessary amount of sunlight. Compared to a two-foot knee wall going around the entire perimeter of the greenhouse, a single north wall of full insulation is approximately just as effective at conserving heat and reducing heating energy demands. Depending on the dimensions of the greenhouse, including the height of the north wall and the length of the greenhouse relative to the width, it may be more effective to have a north wall than a knee wall or vice versa. Of course, having both a knee wall and a north wall is most effective. In some greenhouses, depending on the insulation in the rest of the greenhouse, neither a knee wall nor a north wall of insulation may be cost effective. In modern sustainable greenhouses, insulation is usually built into the initial design. Therefore, adding an insulating knee wall or north wall may be completely unnecessary and not cost effective, since insulation is already in place.

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55 *Ibid*.

56 Simpkins, J. C., D. R. Mears, W. J. Roberts, and J. P. Cipolletti. "Movable Thermal Insulation For Greenhouses." Rutgers. aesop.rutgers.edu/~horteng/ppt/papers/MOVABLECURTAIN.PDF.

57 Focus On Energy. "Ten Easy Ways to Cut Energy Costs In Existing Greenhouse Spaces." Michigan State University. hrt.msu.edu/Energy/Notebook/pdf/Sec3/Ten_Easy_Ways_to_Cut_Energy_Costs_In_Existing_Greenhouses_by_WI_Focus_on_Energy.pdf.

Heat Source

While some modern sustainable greenhouses have been built so that only passive solar energy is needed to provide heat, many greenhouses still require an additional heating source to keep the greenhouse warm, especially at night and in colder months.[58]

One of the most popular kind of heat sources is the gas heater. These heaters are powered by burning fuels such as natural gas or propane and are a reliable way to be able to keep a greenhouse at the necessary temperature. The main drawback is that the heating costs may be a lot depending on the efficiency of the greenhouse, so other heating sources should be considered to see if there is a less expensive alternative.

Another possible heat source is a geothermal heat pump system.[59] A study conducted at the Geo-Heat Center at Oregon Institute of Technology found that heating with geothermal heat pump (GHP) systems would be economically feasible in greenhouses if the cost of natural gas to run a gas heater was sufficiently high.[60] Open-loop GHP systems become economically feasible before closed-loop GHP systems, although they would require a sufficiently large groundwater supply to work.[61] However, even with this groundwater supply, geothermal heat pump systems would probably not be viable in the Santa Fe, New Mexico area in most cases because the cost of natural gas in the area is much lower than the cost needed to make GHP systems viable. Specifically, the Geo-Heat Center study found that if natural gas cost $0.60/therm then an open-loop GHP system could "feasibly be installed to handle 25-30% of annual greenhouse heating demands."[62]

Another source of heat to keep a greenhouse warm at night is the sun. The sun's heat can be stored in the greenhouse by adding thermal mass to the greenhouse. One way to effectively add a lot of thermal mass to the greenhouse is to couple the greenhouse to the earth by adding below-ground insulation under the walls of the greenhouse. Larry Kinney, President of Synergistic Building Technologies, has built a greenhouse in Colorado that only uses the sun to provide all of the heat and lighting that it needs to operate year round.[63] As Kinney says, "Installing insulation around the perimeter of a building between wall insulation and four feet below grade effectively *couples* the structure to deep earth beneath the footprint of the structure. Equally important, it *decouples* the structure from the surface of the earth immediately surrounding the structure, thereby isolating the building from soil whose temperatures vary substantially from season to season."[64] This not only takes advantage of the warm soil four feet below ground, but it also effectively increases the thermal mass of the greenhouse. "The net result is that a thermal bubble builds up under the

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[58] Kinney, Larry. "Greenhouses." Synergistic Building Technologies, Inc. http://www.synergisticbuildingtechnologies.

[59] Chiasson, Andrew. "Greenhouse Heating With Geothermal Heat Pump Systems." Geo-Heat Center. geoheat.oit.edu/bulletin/bull26-1/art2.pdf.

[60] *Ibid.*

[61] *Ibid*.

[62] *Ibid.*

[63] Kinney, Larry. "Greenhouses." Synergistic Building Technologies, Inc. http://www.synergisticbuildingtechnologies.com/greenhouses.html.

[64] Kinney, L, J Hutson, M Stiles, and G Clute. "Energy-Efficient Greenhouse Breakthrough." American Council for an Energy-Efficient Economy. www.aceee.org/files/proceedings/2012/data/papers/0193-000414.pdf.

structure that contributes importantly to the thermal mass of the building, smoothing out the extreme effects of both cold nights and hot days and extending the thermal time constant."[65]

Another source of thermal mass that can be more easily added as a retrofit is water barrels. Water has the highest specific heat of all common materials.[66] Since water has such a high specific heat this means that water can hold the most heat per unit mass of all common materials. Adding one or a few 55-gallon water barrels to a greenhouse is an easy way to add thermal mass to a greenhouse lacking in thermal mass and consequently regulate the temperature of the greenhouse so it does not get as hot or cold during the day or night. There are other containers other than 55-gallon barrels can be used to hold water as well. For example, in large greenhouses heat can be stored in large holding tanks in the order of tens of thousands of gallons.[67] Smaller containers can be used as well, although they may need to be used in large numbers in order to have a significant impact on the temperature inside the greenhouse.

Energy Source

There are a few options to consider when determining the primary energy source of the greenhouse. Most greenhouses, like many other buildings, are powered using electricity from the power grids. It is also possible for greenhouses to work off the grid by utilizing either solar or wind power.

There are clear benefits to using solar energy to power a greenhouse. First, it does not use the power grid, so it is green energy and would not stop working whenever the electricity would stop. For this reason alone, solar energy would be appealing, as it would maintain the greenhouse's proper functions through losses of power. The downside however, is that solar and wind power are both fairly new sources of electricity, so they have not been completely optimized yet.

Another possibility could be to simply work on the power grid. Although it is not considered to be green energy, it is reliable and will constantly provide sufficient energy regardless of the weather. For a greenhouse to be entirely sustainable, electricity is not a great option, but for powering multiple greenhouse functions to help start making it somewhat self-sufficient, electricity could be very useful.

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[65] *Ibid.*

[66] "Specific Heat." TutorVista. physics.tutorvista.com/heat/specific-heat.html.

[67] Burnett, Stephanie E., Brian A. Krug, Neil S. Mattson, Roberto G. Lopez, and Christopher J. Currey. "Heating Solutions: Ten Ways to Heat Your Greenhouse." Cornell Greenhouse Horticulture. www.greenhouse.cornell.edu/crops/factsheets/ten_ways.pdf.

3 Methodology

To achieve the objectives, the team needed to employ many different tactics ranging from archival research to fieldwork. Data was collected regarding the Tesuque Pueblo and the Santa Fe Indian schools' current greenhouses through different types of measurements. This provided information on what areas of the greenhouses needed improvements. From there, the team researched different types of retrofits that would provide the best improvements to the greenhouses and then tested the retrofits on an experimental hoop house. The team's main goal was to help the Tesuque Pueblo and the Santa Fe Indian School by:

- Assessing the efficiencies of the sponsors' greenhouses
- Identifying appropriate retrofits for the sponsors' greenhouses
- Developing an ideal greenhouse design for Santa Fe
- Producing educational resources empowering the community to greenhouse farm

The project applied to the greenhouses and hoop houses in the Tesuque Pueblo along with the Santa Fe Indian School. However, the sustainable designs can help Santa Fe in general and help the community move towards a more sustainable lifestyle. The team collected data from various greenhouses from March 18th till May 3rd, 2013. Final recommendations from the data collected were given to the sponsors and the local community. In the end, the team hoped to provide enough tools that could be used for generations to come to help preserve native cultures and their crops through sustainable greenhouse farming.

3.1 Assessing SFIS and Tesuque Greenhouses

A current issue for both the Tesuque Pueblo and the Santa Fe Indian School is that their farmers don't have a way of measuring the efficiencies of their greenhouses. Without some way to assessing their greenhouses, the communities do not have an understanding of how efficient their greenhouses are and what aspects of the greenhouse can be improved. Because of this ongoing problem, the IQP team worked with the Santa Fe Indian School and the Tesuque Pueblo to analyze their greenhouses. The team created an easily replicated system for analyzing greenhouses, which could be repeated by any farmer. The team's procedure focused on two main aspects of the greenhouses: energy efficiency and cost efficiency.

3.1.1 Taking Readings on Sponsor Greenhouses

Temperature, Humidity, and light intensity inside each greenhouses play a major role in determining what retrofits are needed. In order to figure out how each section of the greenhouse varied in regard to these measurements, the team placed a sensor in four different sections of the greenhouses. The sensor (Onset Hobo u12-012 data logger), seen in Figure 23, measured all three variables. The sensor was placed in 4 sections: north wall, south wall, east wall, and west wall for twenty-four hours each. The measurements taken were compared

Figure 23: Temperature Logger

to the outside weather. The Sensor was placed on all four walls to ensure an accurate assessment of the greenhouse.

Knowing the outside temperature then allowed us to compare the difference in temperature (outside temperature – inside temperature) for both greenhouses. The team could understand how inefficient the heating system is for each greenhouse depending on the outside temperature. Having the graphs with the inside and outside temperature shown together made it simple for the team to find the areas where improvements were needed for each greenhouse.

3.1.2 Assessing Heater Usage at SFIS and Tesuque Calculating Heating Cost of Operation

In order to determine a baseline for how much money the greenhouse at the Santa Fe Indian School costs annually, the team analyzed the overnight temperature fluctuations. Figure 24 shows an example graph of the data collected from the SFIS greenhouse. The team stayed overnight at the SFIS and Tesuque greenhouse and documented each time the heater turned on and off. The team then compared that information with the graphs and highlighted the sections when the heater was turned on. Figure 24 shows a close up of one hour during the night at SFIS. The red portion of the graph shows how many times the heater turned on in that hour.

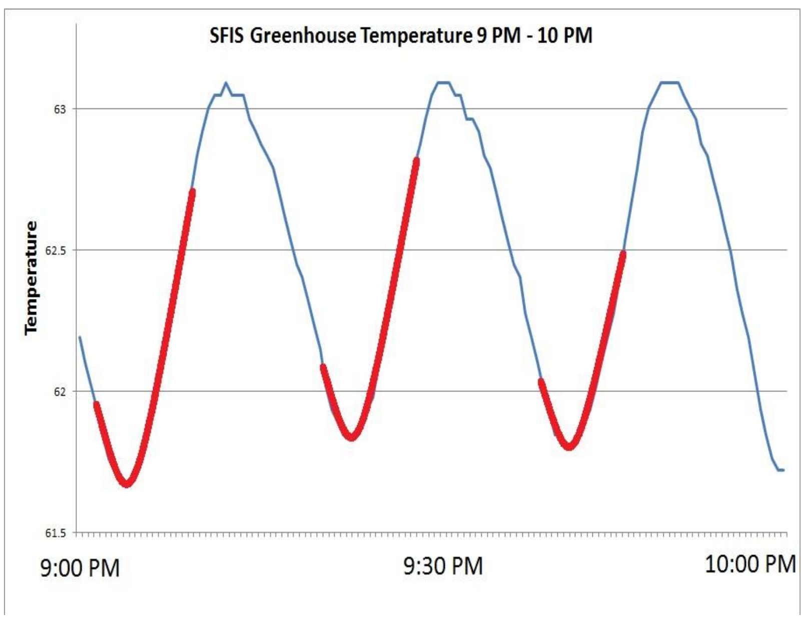

Figure 24: Heater Usage

The same procedure was done on the Tesuque greenhouse overnight graphs. Knowing how many minutes the heaters stayed on, how many times the heater turned on in one hour, and the temperature outside, the team could determine the percentage of time the greenhouse is being heated to maintain the inside temperature depending on the outside temperature. Next, the team analyzed many other nights with a wider range of outside temperatures to understand if the heater usage increased or decreased. Once that was determined, the team could create a baseline of information to figure out the total cost of operation to heat the greenhouses.

Additionally, understanding the heater usage was a way to understand the inefficiency of each greenhouse. As mentioned before, a sustainable greenhouse has limited active technology such as a unit heater. The heaters at SFIS and Tesuque give off 125,000 Btus/hr, which is a substantial amount. Knowing how often these heaters are utilized currently, provides an understanding of how the heater usage can be changed in a positive way. Adding certain retrofits will provide ways to change the current heater usage, and possibly provide a way to cut back on the amount of active technology needed to run the greenhouses. This will make the greenhouses more passive overall and thus increase the sustainability.

3.1.3 Calculating Heating Cost of Operation

To estimate the cost of operation for both the SFIS and Tesuque greenhouses over the course of an entire year, the team utilized a USDA program called Virtual Grower 3.0. Using Virtual Grower, the team was able to simulate the greenhouses and then calculate current costs of operation, overall savings if selected retrofits were added to the greenhouses, as well as compare two greenhouses to each other. This way the team could analyze the SFIS and Tesuque greenhouses in relation to each other. The following steps were taken to simulate the greenhouses and utilize Virtual Grower.

Step 1: Insert the dimensions of the greenhouses, as seen in Figure 25. One must enter the length, weight, height, roof shape, and any other structural dimensions of the greenhouse. The team inserted the correct dimensions for the SFIS and Tesuque greenhouses into the program. The SFIS greenhouse has dimensions of 50ft x 30ft x 15ft, and the Tesuque greenhouse has dimensions of 45ft x 25ft x 10ft.

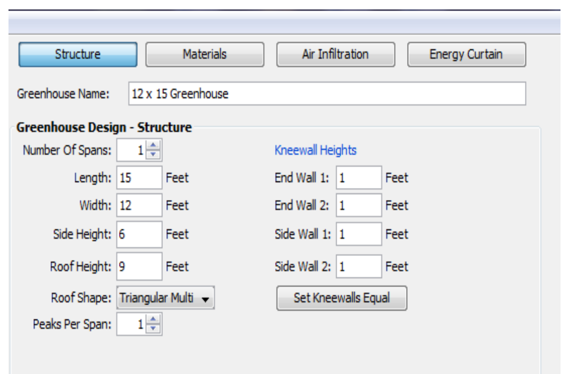

Figure 25: Virtual Grower - Dimensions

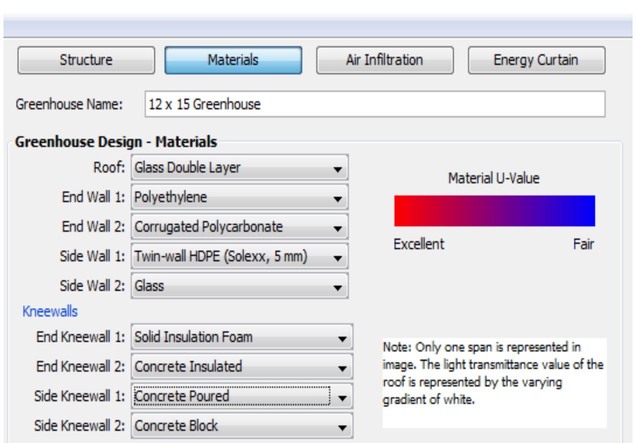

Figure 26: Virtual Grower- Glazing Material

Step 2: Insert the materials including glazing of each individual wall and overall structural material. This process can be seen in Figure 26. The SFIS greenhouse is made of corrugated polycarbonate on all walls, whereas the Tesuque greenhouse is made of single layer polyethylene as the main material but has wooden panels for the ends. The material plays an important role in the total efficiency of the greenhouse so inputted the glazing material into the program ensures accuracy of calculations.

Step 3: The next step is to input the air infiltration, which means the amount of air leaks in both greenhouses. The SFIS greenhouse has less air leaks than the Tesuque greenhouse. Virtual Grower accounts for these differences when calculating overall operation and maintenance costs.

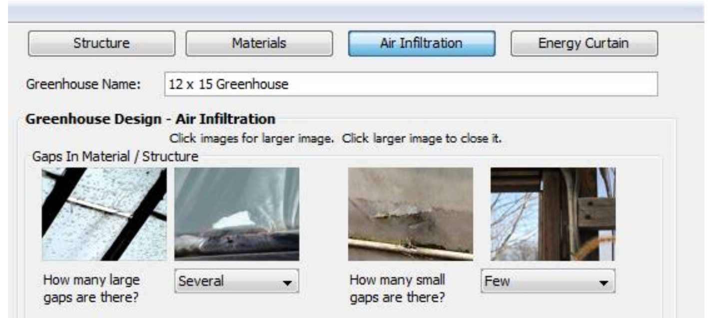

Figure 27: Virtual Grower - Air Leaks

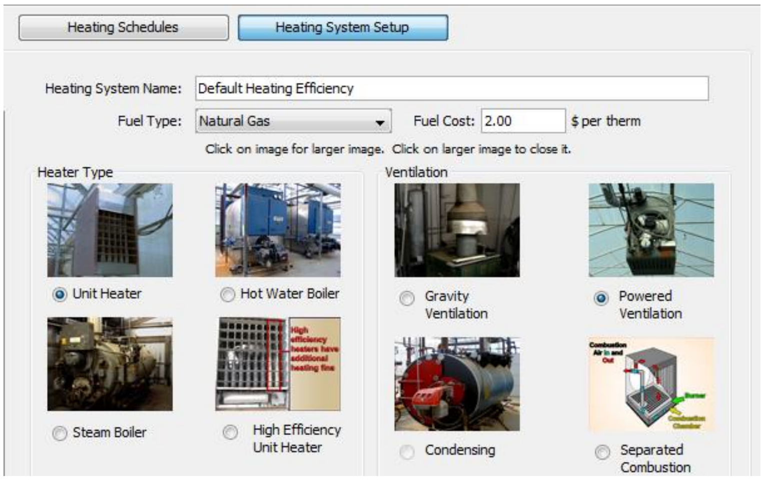

Figure 28: Virtual Grower - Heater Usage

Step 4: The next step in simulating the greenhouses was to select the type of heating system and inputting the heating schedule. The heaters at SFIS are high efficiency unit heaters. The greenhouse itself has a set day and night inside temperatures which were entered into the program. The Tesuque greenhouse only has one unit heater and only one day time temperature. These components are all factored into the final calculations.

Step 5: Once the greenhouses were completely simulated, Virtual Grower will calculate the current operational costs broken down by day, month, and year. The program will also produce a word document highlighting all of the costs as well as pie charts. Once these costs are calculated, one can input different retrofits including complete insulation, energy curtains, knee wall insulation, and changes to heating schedules. The program will then compare these calculation changes to the original calculations and output total savings.

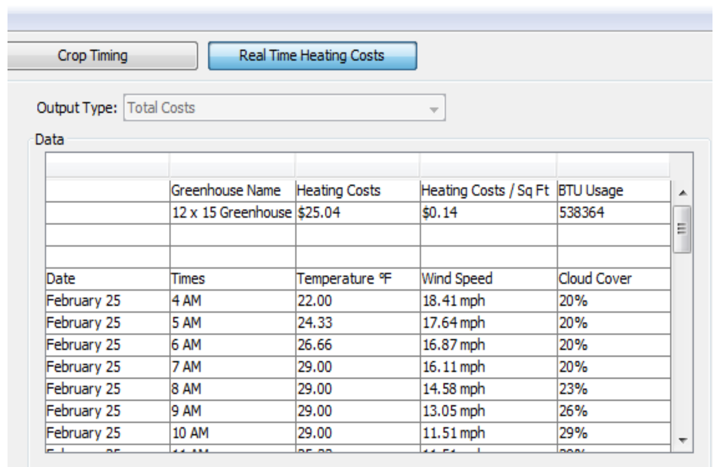

Figure 29: Virtual Grower - Calculations

Therefore, Virtual Grower is an excellent way to assess how selected retrofits will affect the total cost of operation of each greenhouse. The team utilized this program to help determine the current heating cost as well as the benefits of the selected retrofits. The goal was to minimize the total cost of operation by installation of selected retrofits, therefore making each greenhouse more efficient and sustainable.

3.2 Identifying Possible Retrofits for Sponsor Greenhouses

The greenhouses at the Santa Fe Indian School and Tesuque Pueblo needed to be updated making them more efficient in a number of areas including: energy efficiency, cost of operation, amount of sunlight the crops receive, and the temperature inside the greenhouse during different times of the day and seasons of the year. To accomplish this, certain retrofits have been installed. There is a wide range of possible retrofits that can be implemented, ranging from adding insulation to the greenhouse or creating a higher thermal mass inside the greenhouse. Some retrofits are expensive to install or operate, while others are inexpensive. Some retrofits provide tremendous benefits while others only slightly improve the efficiency of the greenhouses. We therefore needed to determine which retrofits would be appropriate to install in the greenhouses at the SFIS and Tesuque Pueblo. Multiple methods were used to determine which retrofits were appropriate, which will be discussed below.

3.2.1 Isolating Greenhouse Inefficiencies

It is important that the retrofits we select to recommend to be installed at our sponsors' greenhouses, at the Santa Fe Indian School and the Tesuque Pueblo, address the main areas of waste in the current greenhouses. Therefore, a main part of the process of selecting appropriate retrofits will involve using the efficiency data that we collected and analyzed previously to direct our search for retrofits. For example, if we find that the existing greenhouses do a poor job regulating their temperature, we will search for retrofits that will keep the temperatures from getting too cold at night or too hot in the day. We will use information from our background research as well as information from surveys that we give to select retrofits that will address these areas of inefficiencies. An example of a survey that we created to give to local farmers with greenhouses as well as companies that specialize in creating sustainable greenhouse designs is given in Appendix B.

We asked Larry Kinney, president of Synergistic Building Technologies, some of our survey questions. One Mr. Kinney's keys to building a sustainable greenhouse was to increase the thermal mass of the greenhouse. To do this Mr. Kinney coupled his greenhouse to the earth by insulating the ground underneath his greenhouse, separating the inside foundation from the colder soil. This proved to be an effective way to regulate the inside temperature of the Synergistic greenhouse

Once researched, the team was able to identify the different inefficiencies inside the greenhouses. The team looked for areas of waste such as overuse of heating/cooling, gaps in doorways and glazing, and other sustainable factors. Larry Kinney suggested that the best way to make a greenhouse efficient is to cut back on the areas of waste. Therefore, the team's main goal was to find out how much energy is used to power the greenhouses and then find ways to cut back on the amount of money and energy needed. This would be done by observing and documenting inefficient sections of the greenhouse as well as measuring the amount of time the heaters and coolers are used. From there, specific retrofits can be selected to help make the greenhouses more sustainable.

3.2.2 Identifying and Selecting Retrofits to Address Inefficiencies

The current glazing materials of the SFIS and Tesuque greenhouses do not provide much insulation because corrugated polycarbonate and single layer polyethylene have an R-value of 0.83. Typically, insulated walls have an R-value of R20 – R40. Insulation provides as a barrier between outside and inside temperatures. Different from a conductor which transfers the heat from hot to cold; an insulator keeps the warm temperature on one side and blocks the cold temperatures on the other side. This is why a well-insulated home stays warm during the winter months when it is below freezing outside. In order to make a greenhouse more sustainable, it should be passive and not need to utilize heaters to keep the inside temperature conducive for farming. Therefore, adding insulation to the SFIS and Tesuque greenhouses is extremely important in making them more sustainable.

Through research, the team narrowed down the type of insulation that would be tested. The goal was to determine low cost options that are easy to install. Having simple solutions would promote sustainability to the local community. The two main areas of heat loss are through thermal radiation to the sky and heat loss to the ground. This can be seen in Figure 30.

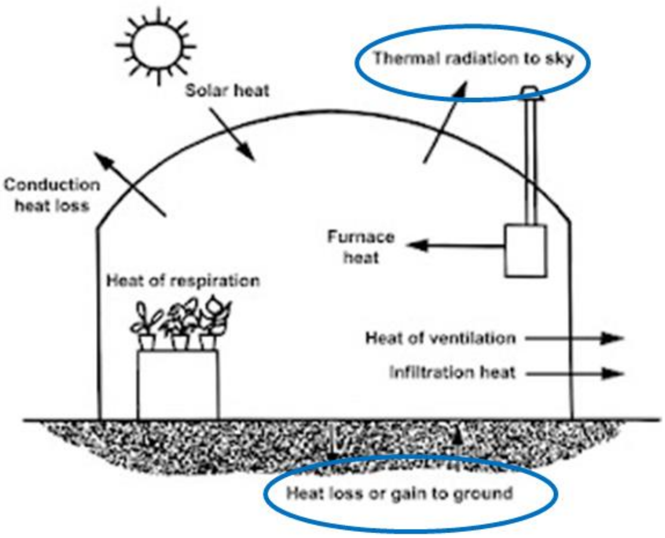

Figure 30: Heat Loss

This knowledge of heat loss focused the team's selection of retrofits. It was decided that roof and ground insulation would be the tested retrofits. For roof insulation, a simple, low cost solution is bubble wrap. Bubble wrap will still allow maximum amount of light into the greenhouse while adding insulation. For ground insulation, a 2 foot knee wall around the perimeter is a good solution because it is easy to install and is relatively low cost. These retrofits were tested on different days and then analyzed to figure out which retrofits had the best results.

3.2.3 Testing Selected Retrofits on Experimental Greenhouse

To test the low cost insulating retrofits, the team built a 20ft x 12ft hoop house at the Tesuque Day School to be the experimental hoop house, which can be seen in Figure 31. The hoop house is completely passive, with only manual ventilation. The greenhouse has two manual vents on each end and two manual flaps, one on either side. The greenhouse being passive made it a good control structure to test the different retrofits.


Figure 31: Experimental Hoop House

After constructing the hoop house, the team placed the Hobo Data Logger inside to take control readings to understand how the hoop house temperature fluctuates throughout the day. The next day, the bubble wrap roof was installed and then monitored using the sensor for 24 hours. The team then deconstructed the bubble wrap roof and installed the 2 ft knee wall around the inside perimeter of the hoop house. Again, this retrofit was monitored using the sensor for 24 hours. Finally, the team reinstalled the bubble wrap roof to find the results of a roof and ground insulation combination retrofit. This retrofit was monitored using the sensor for 24 hours as well. All of these recordings could then be analyzed to determine which had the biggest impact on the hoop house.

3.2.4 Analyzing Benefits and Rating Retrofits

Once all of the testing was done, the team generated an Analysis Matrix to compare each of the retrofits that were physically tested in the experimental hoop house. This matrix, seen in Figure 32, compares Cost with Durability and R-value. The R-value is the insulating value of a material. High quality insulators, like foam, will have high R-values, ranging anywhere from R-7 to R-40 and higher. Durability focuses on the life expectancy of the tested material because if a material is a great insulator but needs to be replaced every year, then it is probably not the most cost effective. Finally, Cost refers to the cost effectiveness of the materials. The team searched for a material that would not only be a quality insulator, but would also be inexpensive to purchase and replace. This matrix was used to find the economical "sweet spot," where the material used was a high quality insulator that would last for an extended period of time and would not be very expensive.

	Roof Bubble Wrap	Knee Wall	Roof & Knee Wall
Cost	○	○	○
Durability	○	○	○
R-Value	○	○	○

Figure 32: Analysis Matrix Template

The team also theoretically calculated how many water barrels it would take to reduce the heater use by one hour at the SFIS and Tesuque Greenhouses. The equation used is shown below:

Specific Heat of Water (Btu/mL^{o}C) * Volume of Water Barrel (mL) * (THigh - TLow)($^{\circ}$C)= # Btus/Water Barrel

From this equation, the team calculated the energy produced by one 55-gallon barrel of water to be 4,580 Btus if the temperature drop 10°Fs. This means that 20, 55 gallon barrels would be needed to supplement an hour of heating in the SFIS greenhouse. 20 barrels would take up a lot of space, but would cut the heating cost by almost 20 percent at the SFIS Greenhouse.

To analyze the benefits of the retrofit testing, the team calculated the cost to use the heater in the SFIS and Tesuque greenhouses theoretically using the USDA program, Virtual Grower. Based on dimensions, shape, and glazing efficiency of the desired greenhouse as well as a description of the heater used in the greenhouse, its efficiency, and the cost of gas per therm for the area, Virtual Grower estimates a 12-

month annual cost of operation. To start, the team estimated the baseline annual cost with each of the greenhouses in their present states.

Once the testing in the hoop house was concluded and the team had decided on an appropriate retrofit to suggest for the two sponsor greenhouses, they tested how efficient a 2-foot knee wall around the perimeter of the greenhouse would be and what the estimated annual savings would be for each of the greenhouses. From both the physical and theoretical tests, the team was able to provide useful data to the sponsors about what needs to be implemented in the greenhouses.

3.3 Identifying an Ideal Greenhouse Design for the Santa Fe Area

The bulk of this project was focused on making recommendations of appropriate retrofits for the sponsors' greenhouses based on the team's assessment of each greenhouse. However, the team also developed details for an ideal greenhouse design for the Santa Fe area that would be inexpensive, energy-efficient and sustainable. The team identified key attributes to consider when designing a greenhouse for the Santa Fe area should the Santa Fe Indian School or Tesuque Pueblo ever want to build a new sustainable greenhouse.

First, the team researched the best practices in sustainable, energy-efficient greenhouses elsewhere in the world. The main approach of developing an ideal greenhouse design for the Santa Fe area was to adapt existing designs that were successful in other parts of the world to the specific climate of Santa Fe. Some aspects of energy-efficient greenhouses could be kept the same in the Santa Fe area, and so they were simply reported in detail for the sponsors' benefit. It was determined that other aspects, such as the materials and insulation, would be better if changed to suit the climate of Santa Fe.

Figure 33: The Tesuque Pueblo Seed Bank, made of alternative insulating materials such as adobe, straw, and used tires.

In addition to considering differing climates, the team considered other factors that are different in Santa Fe, including the building materials available for use and how the different culture would accept the appearance of the greenhouse. Specifically, the team analyzed adobe to determine whether it could effectively be used as insulation substitute for extruded polystyrene insulation used in existing energy-efficient greenhouses in other parts of the country. Data was gathered at the Tesuque Pueblo Seed Bank, pictured in Figure 33, to determine whether adobe and other inexpensive materials found in Santa Fe could be used to effectively insulate a greenhouse as well as other materials. The Seed Bank is passively heated using just the sun and the heat from the earth below the ground.

In addition to adobe, the Seed Bank utilizes used tires in the walls underground to insulate below ground. In a greenhouse it was considered that this technique could be used to create a large "thermal bubble" of warm soil creating a high thermal mass. Used tires were analyzed to see if they could be used effectively for this purpose by examining their physical properties. Additionally, the temperature data from the assessment of the Tesuque Seed Bank was examined to determine whether the used tires worked effectively.

3.3.1 Assessing Efficiency of Adobe as an Insulator

An important aspect of a sustainable, energy-efficient greenhouse is the material used to build the greenhouse. The team performed an assessment of adobe to determine its effectiveness as an insulator and as thermal mass. The team compared its effectiveness to extruded polystyrene Styrofoam insulation to determine whether it could be used as an inexpensive substitute for Styrofoam insulation in the walls of a greenhouse.

Several factors were studied in order to determine whether adobe would work as a substitute for Styrofoam when building an ideal energy-efficient greenhouse in the Santa Fe area. For example, the cost of the two materials was compared. The insulating ability, or R-value, of the two materials was also compared. The specific heats of the materials were compared to determine their relative effectiveness as thermal mass. Finally, the building properties of adobe were noted and examined to see whether they were advantageous enough to justify using adobe as the main building material and as a substitute for extruded polystyrene as insulation for an ideal greenhouse design in the Santa Fe area. The Tesuque Pueblo Seed Bank, which is insulated with adobe, was assessed to determine whether adobe could be used to insulate as effectively as extruded polystyrene.

3.3.2 Assessing Ability of Used Tires to Increase Thermal Mass

In some energy-efficient greenhouses, insulation is used below the ground to turn the soil beneath the greenhouse into thermal mass, as was explained in the Background section of this paper. In order to develop an ideal greenhouse design specific to the Santa Fe area, the team researched the effectiveness of used tires to insulate below ground by examining the tires' physical properties, including specific heat and R-value. The tires themselves were analyzed to see if they would add thermal mass simply by having high specific heat capacities. However, the insulating ability of the tire was also examined because it is the insulation that transforms the soil beneath the greenhouse into a warm "thermal bubble." In addition recycling tires is a more sustainable solution to fiberglass insulation, which is extremely energy intensive in its production. The team then analyzed the Tesuque Pueblo Seed Bank temperature data to see the effectiveness of the tire insulation in that building. In an energy-efficient greenhouse the "basement" of the greenhouse would be completely filled in with soil, unlike in the Tesuque Pueblo, but the data from the Seed Bank was still used to determine the effectiveness of the tires.

Figure 34: Bulky used tires can be seen coated in adobe mud in the basement walls of the Tesuque Pueblo Seed Bank.

3.4 Producing Educational Resources About Greenhouses

In addition to improving the greenhouses at the Tesuque Pueblo and the Santa Fe Indian School, it was the goal of the project team to produce educational resources to help empower the Santa Fe and

Tesuque communities to make their greenhouses sustainable and energy-efficient themselves. To educate the public about greenhouses the team employed several techniques in the hope to inspire the people of Santa Fe and the Tesuque Pueblo to build their own greenhouses and farm locally. The team produced the following tools to help educate the public about how they can assess and improve their existing greenhouses as well as how they can build their own new greenhouses:

- An Educational “Making Your Own Greenhouse” Website
- A “Tips and Tricks” Guide on Features of a Sustainable Greenhouse
- A “15 Easy Steps to Building Your Own Backyard Hoop House” Video

3.4.1 Selecting Useful Tools for an Educational Website on Sustainable Greenhouses

One of the team’s deliverables for the project was an educational website titled “Making Your Own Greenhouse” that describes the history of greenhouses, current practices, how people can build greenhouses themselves, how they can assess the efficiencies of their own existing greenhouses and what retrofits they can install to make them more efficient.[68] The webpage was created by compiling the most important results of the team’s research in each of the areas listed. The topics of the website were chosen by identifying which aspects of the team’s background research would be most relevant to farmers looking to improve their greenhouses. The website also includes recommendations for different retrofits that can be put into a greenhouse, and how to implement them in an easy, efficient, and cheap way. These retrofits were chosen using the team’s recommended retrofits for the sponsors’ greenhouses. Other pages on the website were made using similar considerations. For example, there is a page that talks about current practices of sustainable greenhouses around the world. The greenhouses featured on this page were selected by examining possible greenhouses to see if they stood out as being especially energy-efficient or if they had sustainable features that distinguished them from most other greenhouses around the world.

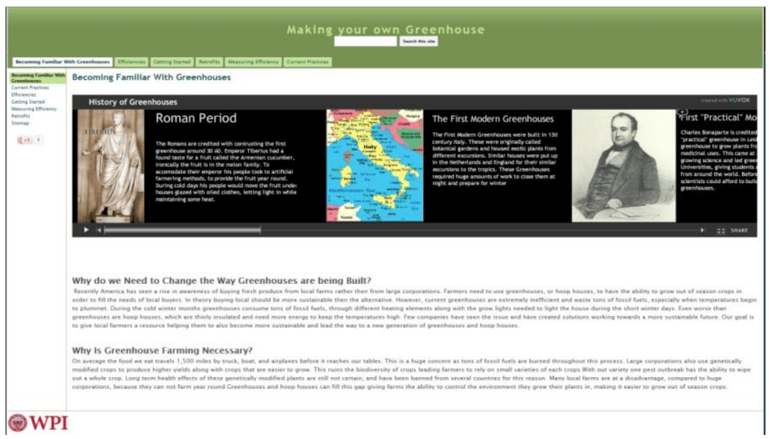

Figure 35: Homepage of Educational Website

[68] "Becoming Familiar With Greenhouses." Making Your Own Greenhouse. https://sites.google.com/site/makingyourowngreenhouse/.

3.4.2 Researching Techniques for a “Tips and Tricks” Guide on Sustainable Greenhouses

Figure 36: “Tips and Tricks to Constructing a Sustainable Greenhouse” Graphic

A “Tips and Tricks” webpage was created making it easier for members of the Santa Fe and Tesuque Pueblo communities to find helpful information about how to make their own greenhouses more sustainable with retrofits.[69] This page has an interactive greenhouse allowing users to scroll over various aspects of a greenhouse leading them to different information and helpful tricks focusing on how to make a greenhouse sustainable. For example, when the user scrolls over the outside material on the greenhouse, a box appears describing which materials the greenhouses are typically made of to make them sustainable. When the user scrolls over the ground insulation, information appears describing tips on how to insulate the structure better to make it more energy-efficient. These key points were determined using the team’s background research and the results of the experiments the team performed while in Santa Fe.

3.4.3 Filming the Construction of a Hoop House to Produce a Video

Another deliverable that the team produced was an education video depicting the construction of a small 20 by 12 foot hoop house. The purpose of the video was to show local farmers exactly how easy it is to construct a greenhouse of their own in their yard. The video was produced by first documenting the construction of the hoop house with over two hundred photographs. The four members of the project team, their sponsor Tony Dorame, members of the Environment Department at the Tesuque Day School, the Director of the Tesuque Department of Agricultural Resources Emigdio

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[69] "Becoming Familiar With Greenhouses." Making Your Own Greenhouse. https://sites.google.com/site/makingyourowngreenhouse/.

Ballon, and several students from the Santa Fe Indian School all helped to construct the hoop house. They built the hoop house at the Tesuque Day School in about two hours, photographing it along the way.

Later, these photographs were used to create a narrated slideshow explaining how to construct the hoop house in fifteen steps. This narration was written using the knowledge that the team had gathered while constructing the hoop house. The program Camtasia was used to produce the final video including the images and narration. The video can be seen on the team's educational website.[70]

[70] "Getting Started." Making Your Own Greenhouse. https://sites.google.com/site/makingyourowngreenhouse/getting-started.

4 Results and Analysis

From the measurements and tests conducted during the preceding sections, the team created many graphs. Using these graphs, they compared both the Tesuque and Santa Fe Indian School's greenhouses along with measuring the energy usage of each greenhouse, providing ideas of different retrofits that would be effective. Next, the group was able to use the results from the experimental hoop house and create different charts comparing how each retrofit compared to the others. After analyzing this information, the team was able to propose different retrofit ideas to both institutions.

4.1 Greenhouse Efficiency Calculations

Understanding the current efficiency of each greenhouse was essential in determining what sustainable designs would improve the efficiency. The team determined the current efficiencies by using the HOBO U12 sensor to measure the temperature, humidity, and light intensity of both greenhouses over various days. The greenhouses needed to be monitored for multiple days because the outside temperature would fluctuate, thus changing the inside conditions. After monitoring the greenhouses, the team determined that the main area of waste was misuse of heaters trying to maintain inside temperatures over night. After this realization, the goal was to figure out exactly how inefficient the greenhouses were, how much the heaters were being used, and how much they currently cost to operate.

4.1.1 Measurements of the SFIS Greenhouse

For a brief overview, the SFIS greenhouse is made of corrugated polycarbonate glazing and is about 5 years old. There are a few main problems with this greenhouse. The largest glazing wall is about 90° off of due south. In fact, there is a cooling "swamp" wall facing due south. Because the orientation is incorrect, the amount of sunlight getting into the greenhouse is limited. Additionally, there are many air gaps around the greenhouse which let in cold air and allow the warm air to escape. The overall specs can be seen in Figure 37.

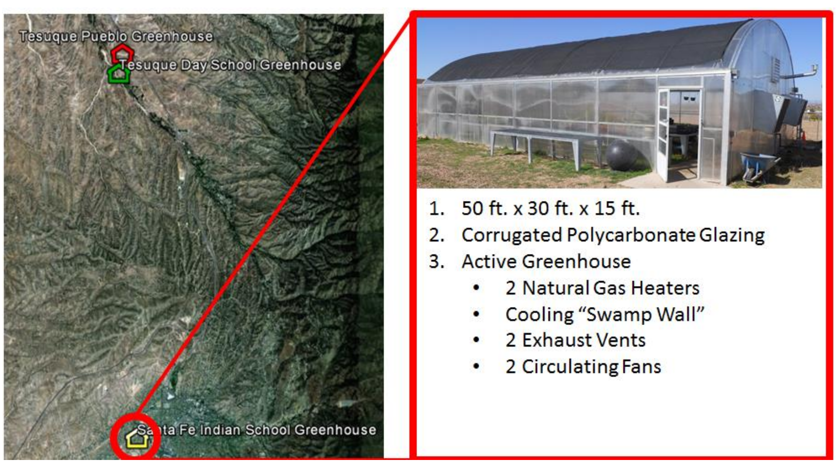


Figure 37: SFIS Specs

The greenhouse has two natural gas heaters that heat the inside. It does have an automatic system, which means there is a thermostat that regulates the use of the heaters and coolers. There is a set day and night time temperature. The heaters, vents, and fans work together to keep the inside at these set temperatures throughout the day. This is a relatively large greenhouse so the heaters have to work hard to produce enough heat to maintain these temperatures. A sustainable greenhouse is completely passive, meaning there isn't any active technology such as heaters and vents. Before the team could identify certain retrofits that would increase the sustainability of this greenhouse, the current efficiency was determined.

Using the temperature sensor, the team could determine the current efficiency of the greenhouse. The sensor monitored the temperature for multiple days. An example of an overnight graph from 3pm – 7 am is seen is Figure 38. The green line shows the inside temperature compared to the blue line which is the outside temperature.

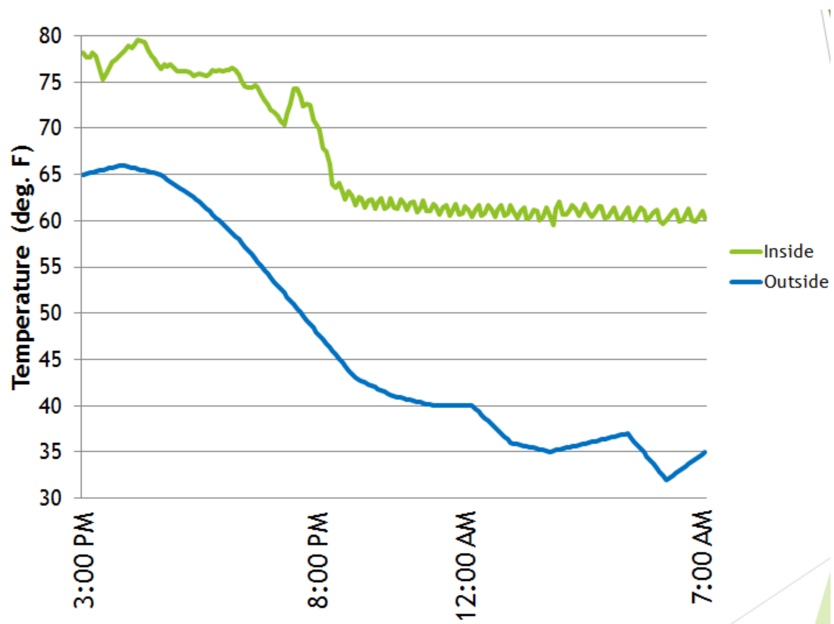


Figure 38: SFIS Overnight Temperature Graph

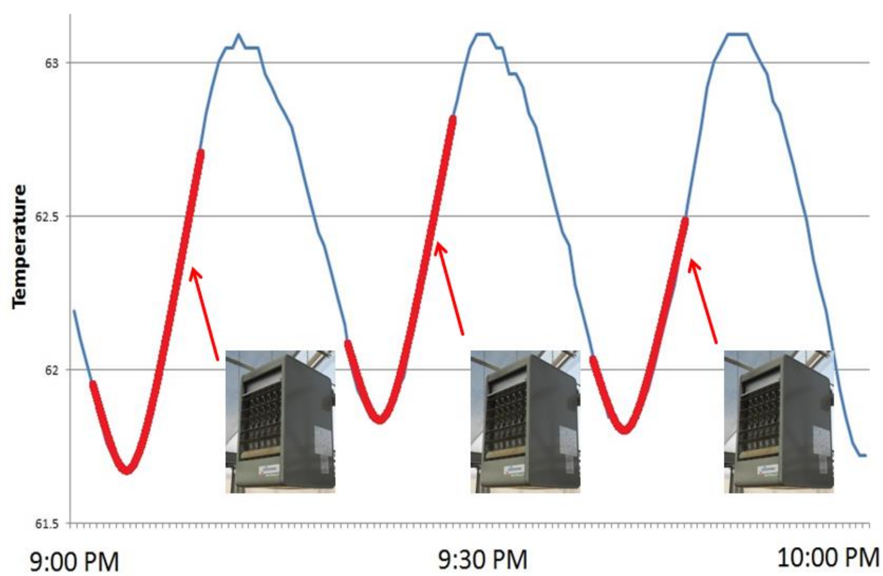


Figure 39: Heater Usage at SFIS

After the sun went down, the inside temperature dropped drastically from around 75° to 62° in a span of about an hour. This proved the greenhouse cannot hold the warm day temperature for very long and will keep dropping as time goes on. When the inside temperature reached 62°, the heaters turned on because that is the night time temperature set by the thermostat. From 8 pm to 7 am, the inside temperature oscillates between 60° and 65°. This is from the heater turning on and off trying to maintain the set temperature of 62°. Although the team could tell the heater was being used often to maintain that temperature, it was unclear how long the heater was on and how long it took for the inside temperature to drop and trigger the heater. The team went to the greenhouse overnight and recorded all the times the heater turned on and off then related those times to the graph. This data can be seen in Figure 39 above.

The heater was turned on for approximately 10 minutes and then stayed off for 10 minutes. The red lines on the graph show exactly when the heater was turned on in that hour span. The heater turned on 3 times in an hour which equates to about 30 minutes. This is 50% of the time. The outside temperature was around 50°. After analyzing data from the other nights the team had monitored the greenhouse, it was determined that the heater was turned on about 4 times per hour when the outside temperature was lower than 40°, but the heater only turned on 3 times per hour when the outside temperature was higher than 40°. Either way, the heater was being used between 40-50% of the night to keep the inside at the set temperature.

The other important realization the team made was how fast the greenhouse lost heat. Looking back at Figure 39, the line when the heater is on and the line when the heater is off have appoximately the same slope. This means the greenhouse loses heat at approximately the same rate it gains it. The team determined that the greenhouse gains 7° in one hour with the heater on constantly, but loses 8° in one hour once the heater is off. This is extremely inefficent and proves the greenhouse does not provide adequate insulation. Some of these facts can be attributed to the air gaps in the corrugated polycarbonate, however this is still a tremendous area of waste. Cutting back on heater usage by adding insulation would help make this greenhouse significantly more efficient.

4.1.2 Measurements of the Tesuque Greenhouse

For an overview of the Tesuque greenhouse, the material is polyethylene glazing, which is more of a film than a sturdy Plexiglas material such as corrugated polycarbonate. The largest glazing wall is about 45° off of due south. The ends of the greenhouse are made of plywood which does not let in light at all. Therefore, the orientation is extremely inefficient. To add to this problem, the black tarp that hangs over the roof as seen in Figure 40 is a shading tarp. This blocks the amount of sunlight penetrating the greenhouse. Additionally, the glazing material is old and is opaque from the UV rays breaking down the material. Therefore, light intensity has declined over the years. Further problems include many tears and open gaps in the material. This lets cold air in and warm air out. This greenhouse is also an active greenhouse. It has one natural gas heater and an exhaust vent. This greenhouse is not as technologically

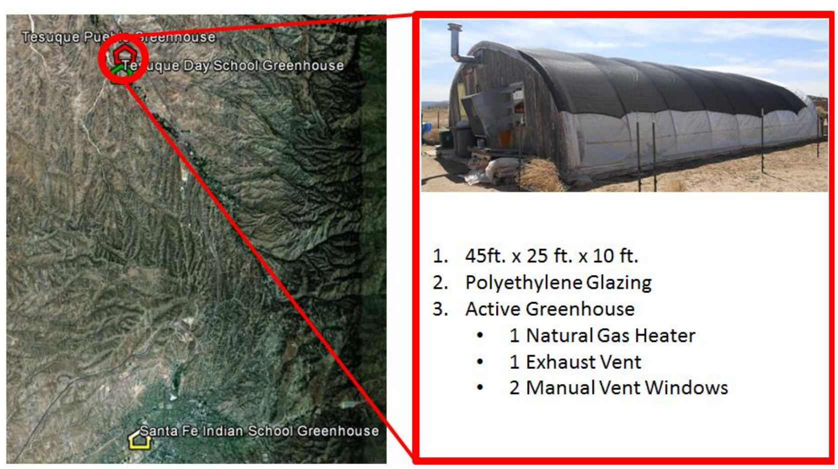


Figure 40: Tesuque Specs

advanced as SFIS. There is only one temperature that can be set on the thermostat. It can be manually changed, but it does not have a set day and night temperature. The overnight graph from 3 pm-7am can be seen in Figure 41. The inside temperature of the greenhouse drops from 100° to 60°, the set temperature, in only 5 hours. This equates to a loss of 8 degrees/hour. Although this is similar to the SFIS greenhouse, the team calculated a 15 degree loss in one hour on a different night. The weather conditions were colder and windier. Therefore, colder air blew into the greenhouse and got trapped inside, thus dropping the inside temperature drastically.

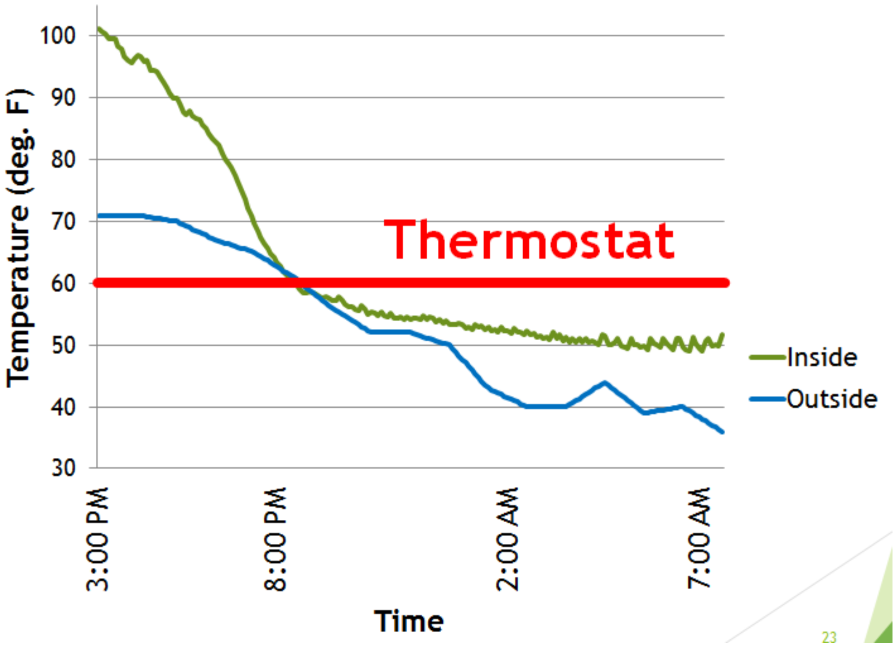


Figure 41: Tesuque Greenhouse Overnight Temperature Graph

The short spikes in Figure 41 indicate the heater being used to try to maintain the inside set temperature. Although the thermostat is set to 60°, the inside temperature, in green, falls well below that set temperature. This can be attributed to two possible causes. The first is that the thermostat is malfunctioning since the graph levels at around 50° on the inside. There is a possibility that the thermostat is just old and working improperly. Another reason is that the heater has a safety feature and will not allow the heater to stay on for an extended period of time. Since the heater can't stay on long enough, it never produces enough heat to maintain the inside temperature. To get a closer look at the Tesuque heater usage, the team stayed overnight at the greenhouse and recorded all the times the heater turned on and off. This close up can be seen in Figure 42 below.

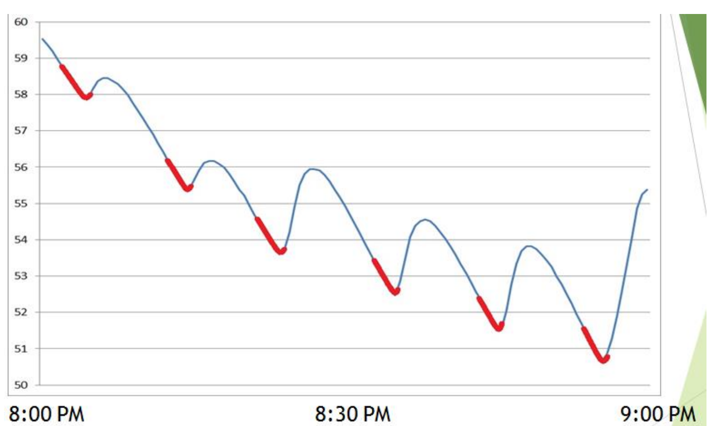


Figure 42: Tesuque Heater Usage

The heater turned on is shown in red. Although the heater turned on 6 times in an hour, it was only on for approximately 3 minutes every time. As compared to the SFIS heater which was on for 50% of the night, this heater is on for only 30% of the night. Even though this seems more efficient, the greenhouse is not maintaining the correct inside temperature, thus it is much less efficient than SFIS. This heater is not being used enough to keep the inside temperature steady. As seen in the graph, the inside temperature still dropped from 60° to 51° in that hour despite the heater turning on 6 times in that hour. This greenhouse is extremely inefficient; however there are many ways to make this greenhouse more sustainable and efficient. Certain retrofits will add insulation to help the greenhouse hold in heat for longer periods of time and hopefully help maintain it's inside temperature. The team's goal is to find ways to make sure the inside temperature does not drop below the outside temperature as well as add retrofits that will help hold the heat for longer periods of time, thus decreasing the need for the heater.

4.1.3 Calculated Heating Cost of Operation

Once the team determined how inefficient both greenhouses were, the next step was determining how much money is used currently to heat these greenhouses. By determining the current cost of operation, one can determine the amount of possible savings from retrofits. In order to calculate the current heater costs of each greenhouse, the team utilized the USDA program Virtual Grower mentioned in Section 3.1.3. Using this program, each greenhouse was simulated and then analyzed. To use Virtual Grower, one inputs the size of the greenhouse, exact location, type of heating system, efficiency of the heater, the schedule of the heater, the cost of natural gas for the region, the current forms of glazing, the amount of air gaps, thus simulating the greenhouse.

For the SFIS greenhouse, the following data was entered into the program:

- Size: 50 x 30 x 15
- Region: 87505 (Indian School Zip Code)
- Type of Heater: high efficiency unit heater
- Heating Schedule: Day Temp: 72° Night Temp: 62°
- Cost: 0.41 dollars/therm
- Glazing: Corrugated Polycarbonate
- Air gaps: Several

Once all of the data was entered, the program calculated the estimated cost of heating for the year, broken down by month. The output is shown in Figure 43. The most expensive month is December, costing over $1,100. Although the SFIS greenhouse is not being operated during the winter months, the goal is to make it a year round greenhouse. Finding ways to cut back on cost would help make this

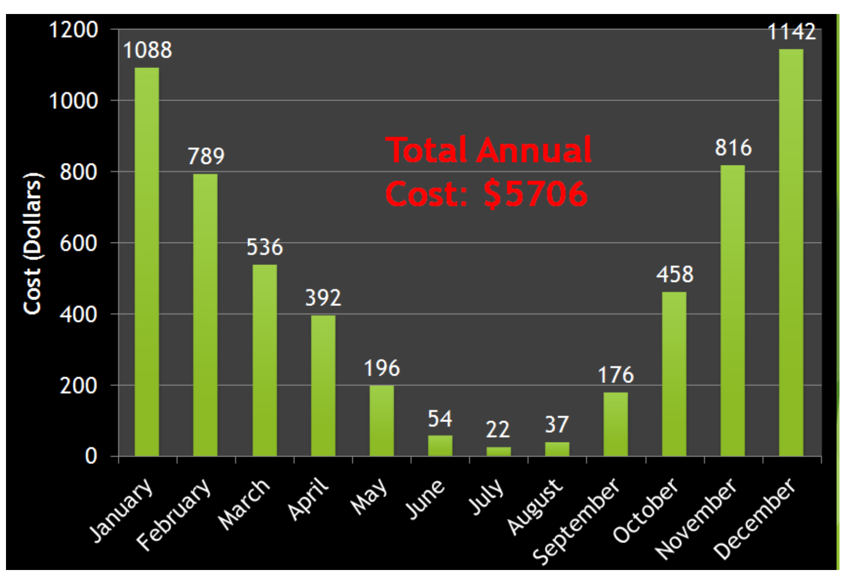


Figure 43: SFIS Greenhouse Annual Cost of Heating

greenhouse capable of operating affordably all year. The estimated overall annual cost is almost $6,000. This is a significant amount and would be a lot lower if the greenhouse was more efficient. By adding retrofits to this greenhouse, it would be able to hold heat longer, decrease the amount of heater usage, and subsequently decrease the total cost of operation.

For the Tesuque greenhouse, the following data was entered into the program:

- Size: 45 x 20 x 10
- Region: 87506 (Tesuque Zip Code)
- Type of Heater: unit heater
- Heating Schedule: Constant Temp: 60°
- Cost: 0.41 dollars/therm
- Glazing: Single Layer Polyethylene
- Air gaps: A Lot

This data was entered into Virtual Grower to estimate the annual costs of Tesuque. These numbers may be more inaccurate than the SFIS data because the Tesuque heater/thermostat are older and may be malfunctioning as previously mentioned. The estimated values per month are shown in Figure 44. Again, the most expensive month is December costing around $700. The overall costs are lower than SFIS. This is because Tesuque only has 1 heater whereas SFIS has 2 heaters. Additionally, Tesuque is a much smaller greenhouse so it takes less power to heat the inside. The estimated overall cost of heating this greenhouse is around $3,300. This is about half of the cost running the SFIS greenhouse. Although it costs less, Tesuque is more inefficient of a greenhouse. The heaters cannot maintain a set temperature, the greenhouse loses heat much faster, the rips and gaps are bigger, and the glazing material is older and opaque resulting in less light penetration.

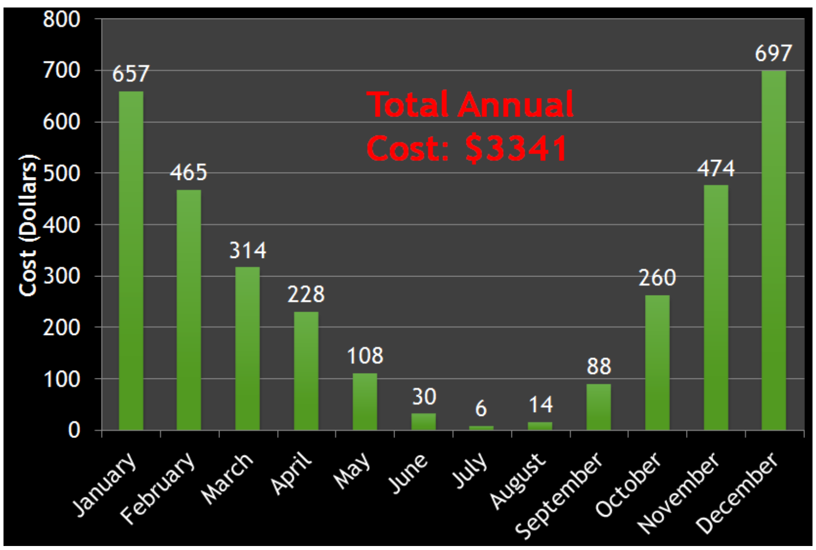


Figure 44: Tesuque Greenhouse Annual Cost of Heating

After completing the first objective: assessing the SFIS and Tesuque greenhouses, the team realized the inefficiencies of both greenhouses. The Tesuque greenhouse is more inefficient than the SFIS greenhouse overall, but both could be greatly improved. In order to be a sustainable greenhouse, it must have mostly passive technology. These greenhouses utilize active technology in the form of heaters and coolers. Although the SFIS greenhouse uses solar panels to power the vents, which is a form of passive technology, the heater is still being overused and run on natural gas. If both greenhouses could move in the direction of using less power to heat and cool the inside, then they will be more sustainable. Unfortunately, both greenhouses are incapable of running on passive technology in their current states. The corrugated polycarbonate and single layer polyethylene do not provide enough insulation to maintain the needed inside temperature overnight. Without heaters, the inside temperature would fall below freezing and kill all of the culturally relevant crops.

The next objective was to determine retrofits that could improve the efficiency of these greenhouses. Because the main inefficiency of both greenhouses is heater usage, the most important types of retrofits are insulation and thermal mass. These two components are necessary to help the greenhouses hold the warm day temperatures and slowly dissipate the heat throughout the night to keep the greenhouse from dropping below freezing. By adding these components, the heaters would not be a necessary component of either greenhouse and thus transform them into more passive, sustainable greenhouses.

4.2 Experimental Retrofit Assessments

To test possible improvements that could be made to each of the sponsors' greenhouses, the team utilized a small experimental hoop house at the Tesuque Pueblo Day School. The group constructed this 20 ft. x 12 ft. x 8 ft. hoop house with the assistance of a few local pueblo members as well as students from the Santa Fe Indian School. Once the polyethylene hoop house was constructed, the team determined which forms of retrofit testing would produce the most positive results for the two greenhouses they were working with. The team determined that insulation was definitely the most important retrofit that needed a focus; particularly prevention of heat loss through the roof and the ground. For this reason, the team decided to use bubble wrap as an insulator for the roof and to construct a two foot high knee wall around the perimeter of the hoop house to add some insulation at the base.

4.2.1 Assessment of Control Day

To begin the testing, the team set up a baseline control day, where nothing was installed inside the hoop house. As can be seen by the graph in Figure 45 from temperature readings overnight on the control day, the hoop house's inside temperature dropped below the outside temperature and stayed well below the outside temperature throughout the course of the night.

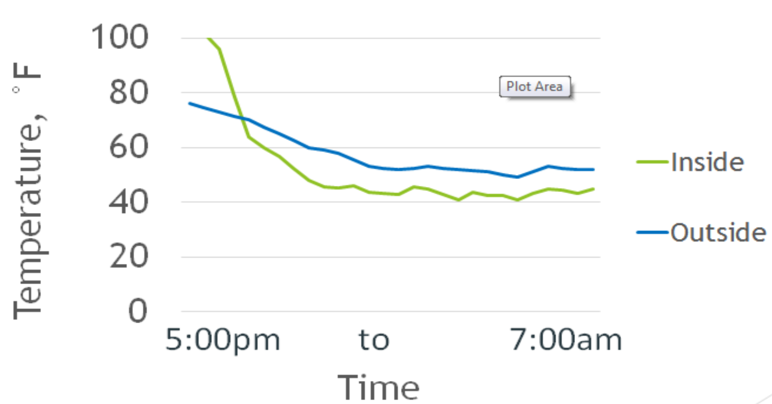


Figure 45: Inside vs. Outside Temperature Control Day

Although this data was surprising at first, further research proved that it was not uncommon for kit hoop houses, such as the one constructed, to have similar problems. There are two likely causes for data such as this. One possible reason is that since kit hoop houses have multiple large gaps between the frame and the glazing material, it is very easy for wind to blow cold outside air into the hoop house and result in the cold air being trapped inside. For an area such as Santa Fe, where the winds can be very strong, this is a very possible reason for results such as these. Another potential cause was because the breeze outside mixed with the air reducing the radiative cooling in the atmosphere. Although, the hoop house has multiple air leaks, the covering does provide some satisfactory protection from the wind, which in this case, is actually detrimental to the hoop house because it does not allow for the same radiative cooling inside.

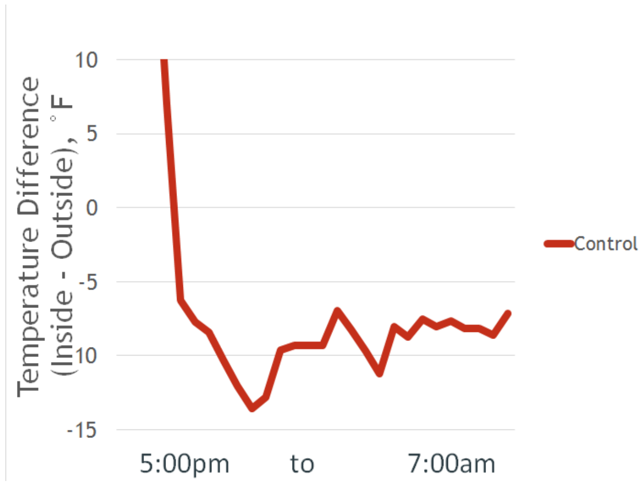


Figure 46: Inside vs. Outside Temperature Difference Control Day

To show the difference in temperatures throughout the duration of the night, the team graphed the delta value between the inside and outside temperatures, as can be seen in Figure 46. From the graph, the team determined that the temperature dropped to nearly 15^{o}F below the outside temperature at the beginning of the night, and remained approximately 10^{o}F below the outside temperature throughout the course of the night. Although the control day was expected to be the worst performing day of all the testing days, the group did not expect the temperature to drop below the outside by so much and remain there for the entire night. The other testing days became very important to the team because at the very least, the hoop house should be more consistent with the outside temperature.

4.2.2 Assessing Bubble Wrap Roof

For the second day of testing, the group installed approximately 225 square feet of ½” bubble wrap on the roof of the hoop house. Bubble wrap is a very inexpensive insulator, costing only about $0.19 per square foot. The only real detractors of bubble wrap insulation are that it is not very durable, it would need to be replaced every year or two, and it does not have a very high insulating value, with an R-value of only around 1.1.

When the bubble wrap was tested inside the greenhouse however, it revealed some pretty exciting results for the group. The results of this test are shown below in Figure 47.

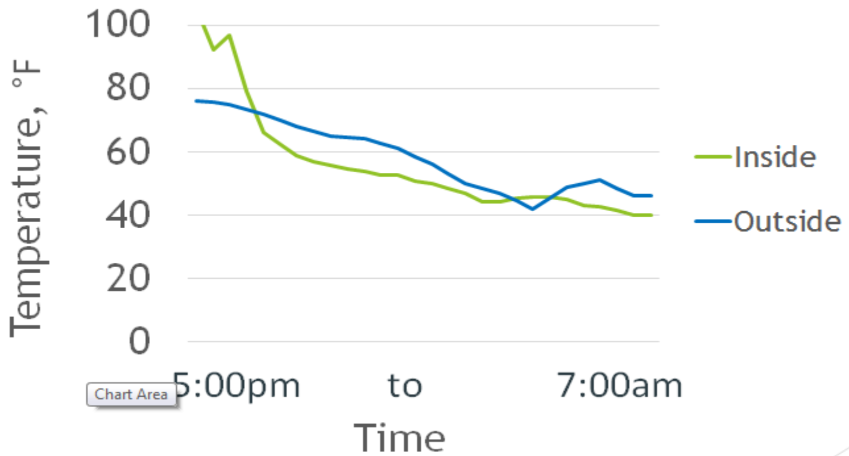


Figure 47: Inside vs. Outside Temperature Bubble Wrap Roof

The group discovered that even though the temperature inside the hoop house had dropped below the outside temperature for most of the night, it not only stayed significantly closer to the outside temperature, but also did not lose temperature at nearly as fast of a rate as the control day. For an insulating material considered to be rather cheap and weak, bubble wrap provided the team with quality results and proved that it could be considered a quality insulator for farmers on a budget. The bubble wrap provided a much more controlled temperature decrease throughout the course of the night, especially when there were points with elevated wind gusts that could have had very adverse effects on the hoop house.

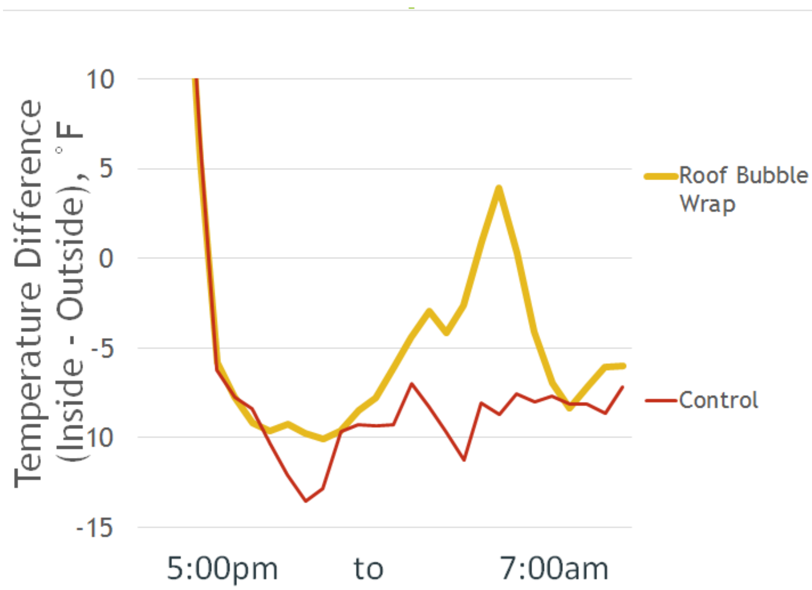


Figure 48: Temperature Difference Bubble Wrap vs. Control

Looking at the temperature difference graph compared to the control day in Figure 48, it is evident that the bubble wrap was a significant improvement from the control. The temperature dropped to approximately 10°F below the outside at the beginning of the night, but continued to drop at a slower rate than the outside temperature until it was eventually warmer inside the hoop house than outside.

To fill out the Analysis Matrix mentioned in section 3.2.4, the team ranked the bubble wrap to the other tested retrofits. Since the bubble wrap was the least expensive at only \$0.19/sq. ft., but it is neither the most durable nor the most insulating material tested. For these reasons as seen in Figure 49, the bubble wrap received the highest score in cost effectiveness, but the lowest in both R-value and durability.

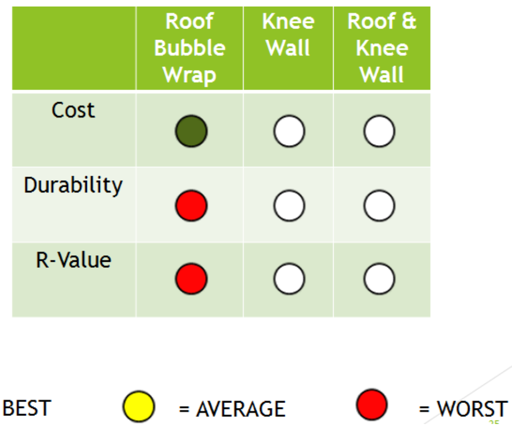


Figure 49: Analysis Matrix - Bubble Wrap

4.2.3 Assessing 2 Foot Knee Wall Insulation

On the second day of testing, the group installed a knee wall about two feet high around the inside perimeter of the hoop house. The intention of a knee wall is to add insulation at the base of a hoop house or greenhouse where cold air settles. Also, the knee wall can be effective in preventing cooling from the wind. The knee wall was slightly more expensive than the bubble wrap was, at a price of \$6.20 for a 2 ft. x 4 ft. sheet, or roughly \$0.78 per square foot. Although it is more expensive, the Styrofoam insulation used to make the knee wall has an R-value of over 7 times the value of the bubble wrap at R-7.7. Additionally, the insulation has a much longer lifespan as it is not affected by UV radiation from the sun as much as the bubble wrap.

The testing results of the knee wall showed a graph that can be seen in Figure 50. The graph shows that the knee wall performed even better than the bubble wrap by itself, which was to be expected. The temperature inside the hoop house lost temperature much more slowly than it had either of the previous two days and was almost equal to the outside temperature for the entire night.

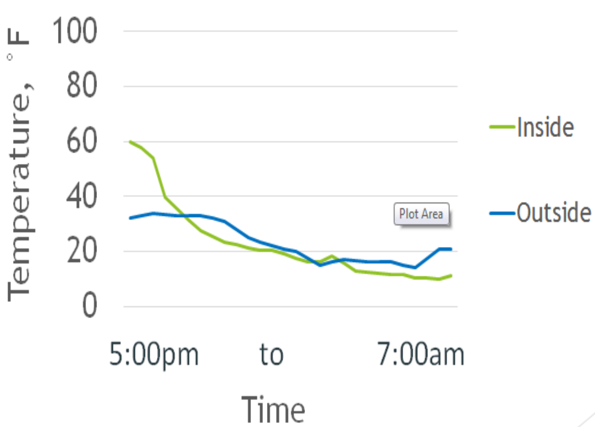


Figure 50: Inside vs. Outside Temperature Knee Wall

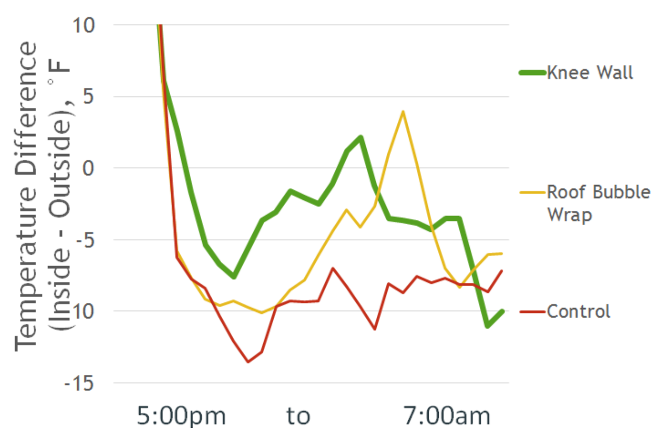


Figure 51: Temperature Difference Knee Wall

This data was also impressive because the wind outside the hoop house was very strong, with sustained winds of nearly 20 miles per hour. Looking at the temperature difference graph in Figure 51, the knee wall insulation, shown in green, by comparison to the bubble wrap and control testing days, was the best performer. The roof buble wrap is shown in yellow and the control is shown in red. The knee wall maintained a less negative difference between inside and outside temperature. The knee wall even maintained a higher inside temperature than outside temperature for a portion of the night. Overall, the temperature inside the greenhouse stayed within 5^{o}F of the outside temperature for nearly the entire night. This shows that the knee wall was highly effective in retaining the heat throughout the night.

To continue with the Analysis Matrix in Figure 52, the knee wall characteristics were added to the chart. The knee wall is more expensive than the bubble wrap, but it is also a much better insulator and last substantially longer than the bubble wrap does. Since it was better than the bubble wrap in both Durability and R-value, the knee wall insulation received a color denotion of yellow, or “AVERAGE,” since it still was not the best performer in those categories. Additionally, the insulation received a lower cost score than the bubble wrap since it was more expensive to purchase and install. Overall, the knee wall provides more insulation which was the ultimate goal of the retrofit.

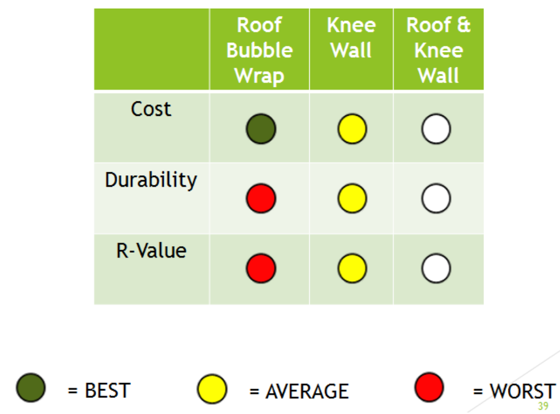


Figure 52: Analysis Matrix - Knee Wall

4.2.4 Assessing Roof Bubble Wrap and Knee Wall

For the last day of testing, the group combined the previous two retrofit ideas, by using both the bubble wrap on the roof as well as the knee wall. Since the two were combined, the cost is $0.97 per square foot. By utilizing both of the retrofits, the team felt that the hoop house would not only be able to block the wind and cold air at the base of the greenhouse, but also prevent severe thermal radiation through the roof. For this reason, the team expected this combination to be the most effective method for the experimental hoop house.

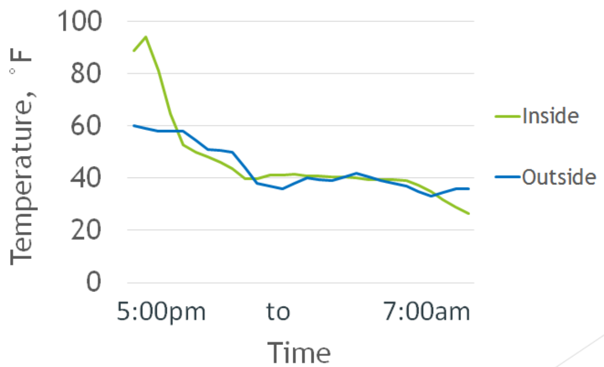


Figure 54: Inside vs. Outside Temperature Knee Wall and Bubble Wrap

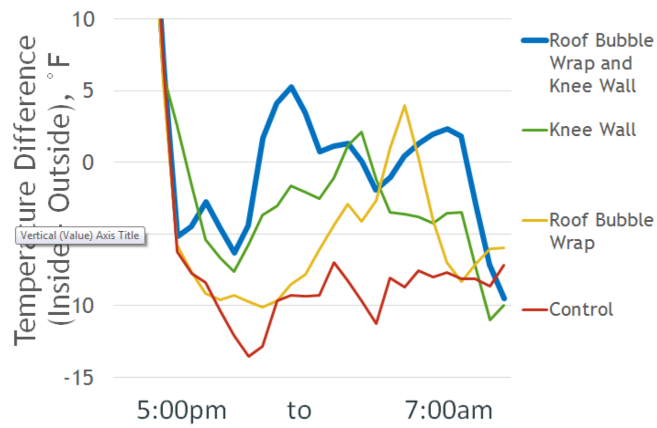


Figure 53: Temperature Difference Knee Wall and Bubble Wrap

From the graph in Figure 54, the team confirmed their hypothesis that combining the bubble wrap with the knee wall would be the most effective retrofit. Although the temperature dropped fairly quickly as the night began, it almost never dropped below the outside temperature, staying roughly even with it for the entire night. Although the hoop house was not kept at an ideal temperature on any of the days, this particular day of testing proved to be the most beneficial for the hoop house's performance.

Looking at the temperature difference graph in Figure 53, it is clear that the day of testing involving both the bubble wrap and the knee wall was the most effective. As was previously mentioned, the temperature inside the greenhouse stayed roughly equal to the outside temperature for the entire night. The inside temperature even reached over 5°F above the outside temperature at one point.

Going back to the Analysis Matrix, the bubble wrap and knee wall combination received the lowest score for cost effectiveness, but it had the best insulation, so it received the highest score for R-value. Since the insulation and knee wall are only as durable as the indivual components, the durability score was rated as average. Despite the fact that it is the

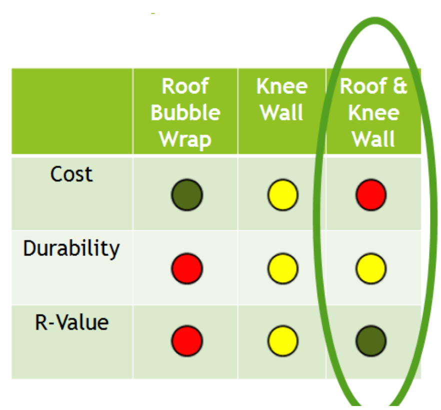


Figure 55: Analysis Matrix - Bubble Wrap Roof and Knee Wall

most expensive, the retrofits are both inexpensive enough for the improved efficiency of the hoop house to be worth the investment and for that reason, the team selected the combination of a bubble wrap roof with the 2 foot knee wall to be the best selection of an appropriate retrofit for the experimental hoop house.

4.2.5 Assessment of Water Barrels as Thermal Mass

Due to time and budget constraints, the team was not able to experimentally test the effectiveness of using water barrels as thermal mass in the experimental Tesuque Day School hoop house. However, in an effort to determine whether water barrels would be an effective retrofit, a few calculations were made to determine how much heat water barrels could store from the day to provide to the greenhouse at night.

First, the specific heat of water, 4.18 J/(g*°C) was converted to units of BTU/(55-gallon-barrel*°F):

$$Specific\ Heat\ Water\ = 4.18\ \frac{J}{g * °C}$$

$$= 4.18\ \frac{J}{g * °C} * \frac{1\ BTU}{1055\ J} * \frac{3785\ g\ Water}{1\ gallon\ Water} * \frac{55\ gallons}{1\ Barrel} * \frac{1\ °C}{1.8\ °F} =$$

$$Specific\ Heat\ Water = \mathbf{458}\ \frac{\mathbf{BTU}}{\mathbf{Barrel} * \mathbf{°F}}$$

In other words, each 55-gallon water inside a greenhouse would release 458 BTU of energy into the air per degree Fahrenheit that the water temperature dropped as the greenhouse cooled from the day to night.

To compare this amount of energy to more familiar terms, the heater inside the Santa Fe Indian School greenhouse outputs about 93,000 BTU/hour. If it is assumed that the water barrels would drop 10°F in temperature going from the day to night then the number of water barrels to make up for one hour of heater use can be calculated:

$$\frac{93{,}000\ BTU}{\frac{458\ BTU}{°F} * 10°F} = 20.3\ Water\ Barrels\ for\ One\ Hour\ of\ Heater\ Use$$

However, this is a conservative estimate. In reality, the temperature inside the greenhouse on an average day in the month of April reaches almost 100°F and at night drops to about 60°F. If we assume that the temperature of the water in the water barrels reach 90°F before dropping down to 60°F before the end of the night, then the number of 55-gallon water barrels necessary to make up for one hour of heater use would actually be much smaller:

$$\frac{93{,}000\ BTU}{\frac{458\ BTU}{°F} * 30°F} = 6.8\ Water\ Barrels\ for\ One\ Hour\ of\ Heater\ Use$$

It should be noted that at the Tesuque greenhouse the heater produces less heat per hour than the SFIS greenhouse and therefore the number of water barrels necessary to substitute for one hour of heater use may be even less.

Due to the fact that there is sufficient space in each of the sponsors' greenhouses to accommodate a few to several water barrels, adding water barrels as thermal mass is likely to be a good way to regulate the temperature so that it does not get to hot during the day and so that more of the heat from the day can be saved for the night after the sun goes down, to reduce the amount of heater use needed to maintain the greenhouse at the night temperature. Also note that if the water barrels are used as table legs for the tables that the plants grow on in the SFIS greenhouse and the Tesuque greenhouse, then it may be possible to have many water barrels in each greenhouse with taking up space that would otherwise be used for plants.

4.3 Educational Resources About Greenhouses

The project team produced educational resources to help empower the Santa Fe and Tesuque Pueblo communities to make their greenhouses more efficient themselves. Several resources were produced to help accomplish this goal that educate users about sustainable greenhouses and how to effectively build them. The resources give information about different kinds of efficiencies and why each is important to the overall design of the greenhouse. The educational resources also provided users with information depicting not only how they can build their own greenhouses, but also how their existing greenhouses can be retrofitted and made more sustainable. The three different tools created to complete this objective were:

- An Educational “Making Your Own Greenhouse” Website
- A “15 Easy Steps to Building Your Own Backyard Hoop House” Video
- A “Tips and Tricks” Guide on Features of a Sustainable Greenhouse

4.3.1 “Making Your Own Greenhouse” Educational Website

The team produced an educational website for the Santa Fe and Tesuque community titled “Making Your Own Greenhouse.”[71] This website consists of several webpages containing a wide variety of information about sustainable, energy-efficient greenhouses. These webpages are discussed in more detail below.

Homepage

The homepage of the educational website features a timeline of the history of greenhouses from the first ever greenhouses during the Roman Period to modern examples of sustainable, energy-efficient greenhouses. There are pictures and captions on the timeline that link to further information. The timeline explains how greenhouses have

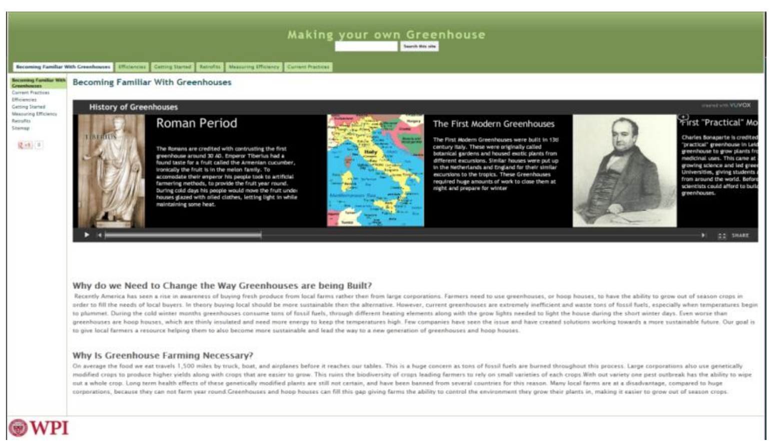


Figure 56: Homepage of Educational Website

[71] "Becoming Familiar With Greenhouses." Making Your Own Greenhouse. https://sites.google.com/site/makingyourowngreenhouse/.

evolved in structure and use over time. The homepage also explains why greenhouse farming is necessary and why the way that greenhouses are built needs to be changed so that they can use less energy, water, space, and money.

Getting Started

Embedded into the "Getting Started" page of the educational website is the "How To Build Your Own Backyard Hoop House in 15 Easy Steps" video deliverable, which is described in detail in Section 4.3.3 of this paper. The webpage also contains links to stores where kit greenhouses can be purchased, including the specific hoop house that is depicted being constructed in the video.

Figure 57: "Getting Started" Page of Educational Website

Retrofits

The "Retrofits" page contains information on several common retrofits that can be added to a pre-existing greenhouse. The featured retrofits include shading nets, energy curtains, insulating shutters, light shelves, and trombe walls, among other retrofits. Next to each retrofit is a picture depicting what the retrofit looks like as well as a short description of each retrofit. Each retrofit is also linked to another webpage where you can either buy the product or get more information about how the retrofit works.

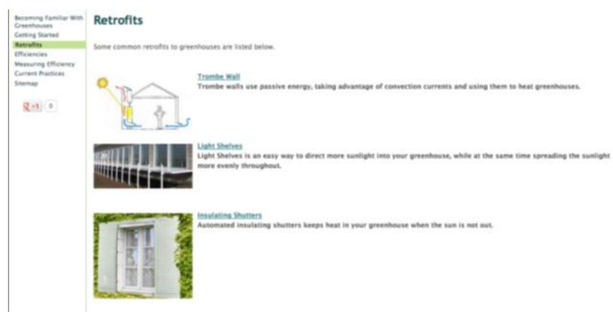
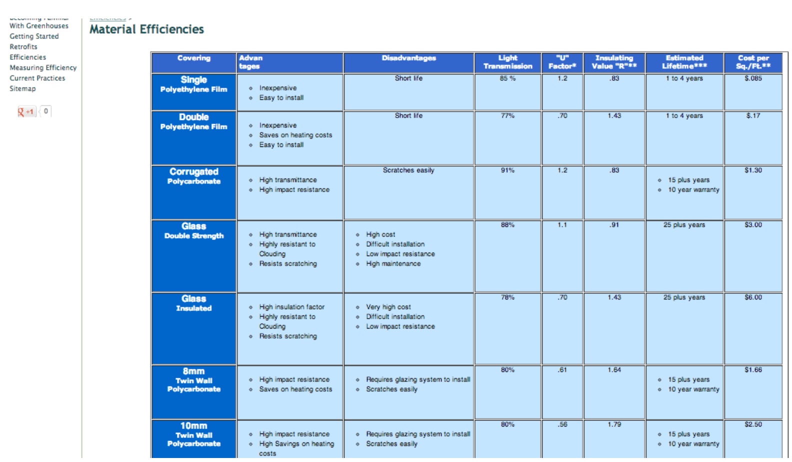


Figure 58: "Retrofits" Page of Educational Website

Efficiencies

The "Efficiencies" page of the educational website contains the "Tips and Tricks" guide, which is discussed in greater detail in Section 4.3.2 of this paper. The webpage also contains four subpages that go into the specifics of energy, water, site, and material efficiencies. The energy efficiency page contains a link to a checklist that provides an easy way for farmers to make sure they are utilizing their greenhouse in the most efficient manner. The page also includes information links about insulation, ventilation, and step controllers. These are three easily implemented ways to make sure



Material Efficiencies

Covering	Advantages	Disadvantages	Light Transmission	"U" Factor*	Insulating Value "R"**	Estimated Lifetime***	Cost per Sq./Ft.**
Single Polyethylene Film	Inexpensive; Easy to install	Short life	85 %	1.2	.83	1 to 4 years	$.085
Double Polyethylene Film	Inexpensive; Saves on heating costs; Easy to install	Short life	77%	.70	1.43	1 to 4 years	$.17
Corrugated Polycarbonate	High transmittance; High impact resistance	Scratches easily	91%	1.2	.83	15 plus years; 10 year warranty	$1.30
Glass Double Strength	High transmittance; Highly resistant to Clouding; Resists scratching	High cost; Difficult installation; Low impact resistance; High maintenance	88%	1.1	.91	25 plus years	$3.00
Glass Insulated	High insulation factor; Highly resistant to Clouding; Resists scratching	Very high cost; Difficult installation; Low impact resistance	78%	.70	1.43	25 plus years	$6.00
8mm Twin Wall Polycarbonate	High impact resistance; Saves on heating costs	Requires glazing system to install; Scratches easily	80%	.61	1.64	15 plus years; 10 year warranty	$1.66
10mm Twin Wall Polycarbonate	High impact resistance; High Savings on heating costs	Requires glazing system to install; Scratches easily	80%	.56	1.79	15 plus years; 10 year warranty	$2.50

Figure 59: "Material Efficiencies" Table on Educational Website

your greenhouse saves the most possible energy. The material efficiency page includes a chart comparing eight glazing materials. The chart includes each materials costs, lifetime, R-value, and light transmission. Next, the site efficiency page contains all necessary steps and precautions that must be taken into consideration when orienting a greenhouse. Lastly, the water efficiency page include three links that take the user to different websites that allow the user to find information on how and where to buy different watering systems.

Measuring Efficiencies

The next page on the educational website contains about how to measure the efficiency of a greenhouse. The first links bring the user to the download page of the Virtual Grower 3 program and the second link brings the user to the Onset Data Logger sensor that the project team used for their assessments and experiments. Virtual Grower 3 is a USDA created software that allows its user to simulate their exact greenhouse by inputting its exact size and shape, heating system, materials, insulation, and other attributes. The program then generates an estimate of the yearly cost to operate the user's greenhouse and breaks this estimate down by month using past weather statistics. Users can then add insulation and several other possible retrofits to their greenhouse get an estimate of how much money they could possibly save.

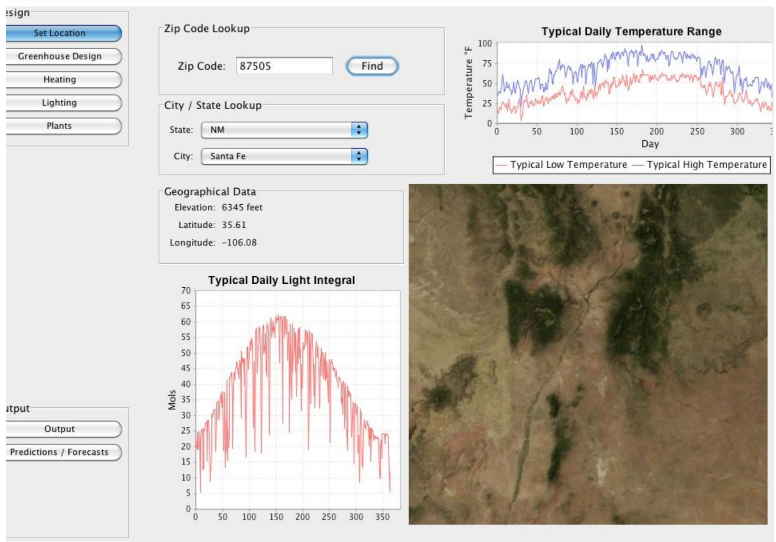


Figure 60: Virtual Grower Greenhouse Simulation Program

Current Practices

The "Current Practices" page of the educational website is the last page on the website as of the publishing of this paper. The webpage focuses on current sustainable farming practices around the world involving greenhouses or other controlled environments such as biodomes. This section has pictures and short introductions to Four Seasons Farms, Synergistic Building Technologies, Biosphere 2, Eden

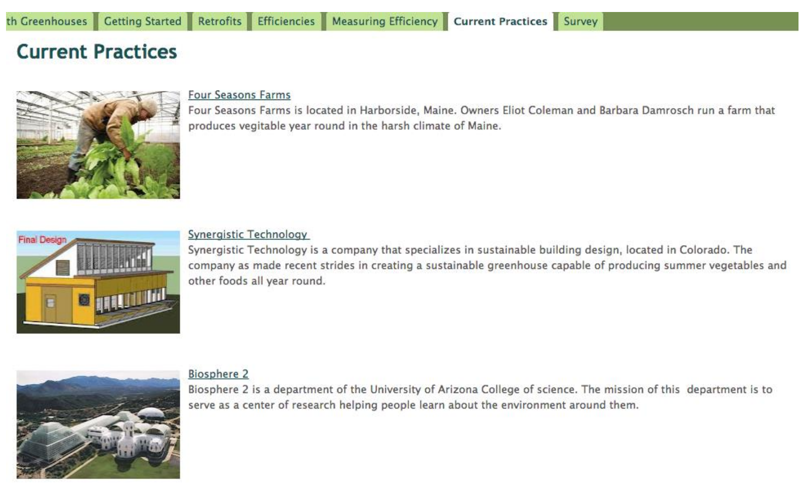


Figure 61: "Current Practices" Page of Educational Website

Project, Thanet Earth, and The Sahara Forest Project. Each title is linked to the website where the user can get the most information about the project.

4.3.2 "Tips and Tricks" Guide To Building a Sustainable Greenhouse / Hoop House

Next the team developed a model of a greenhouse. When the user rolls his or her cursor over the model an information box is filled out with a quick overview on different effeciencies. This tool allows the user to get familiar with the different types of effeciencies and variables that go into greenhouse constructing, before diving deeper into the website. This guide covers seven different aspects to consider when building a greenhouse:

- Material Efficencies
- Production Efficencies
- Water Efficencies
- Site Efficencies
- Insulation
- Ventillation
- Energy Source

Material Efficency

The roll over of material efficencies gives general information on how to choose a glazing material for your greenhouse. For example the information box tell the user to look at aspects of the glazing material such as cost, insulating qualities, light transmission properties, and durabilty of the product. The most common of the glazing materials are known to be different varieties of polyethylene, polycarbonate, and glass.

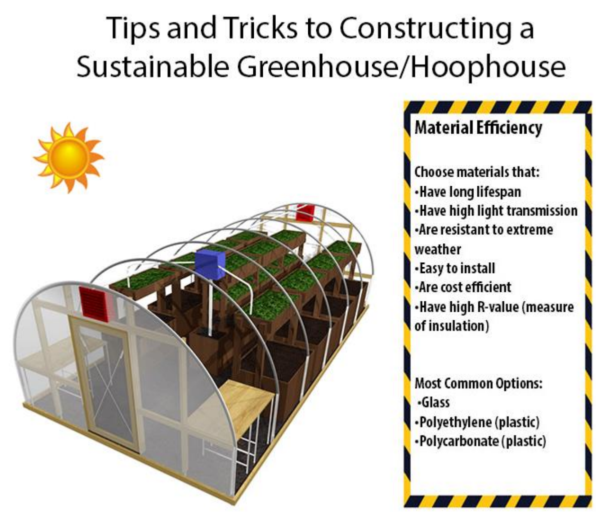


Figure 62: Tips and Tricks - Material Efficiency

Production Efficiency

The model also gives the user planting tips, telling the reader how to place their plants inside the greenhouse. The diagram also stresses how to ventilate your greenhouse to rid the area of mildew and different types of fungi. The farmer should also know to use fertilized soil and to place plants where they can get direct sunlight. The next step of production efficiency is to properly utilize all the space inside the greenhouse. The diagram talks about using three different layers for planting. First is the ground layer where plants should be put directly into the ground or in pots if the ground

Figure 63: Tips and Tricks - Production Efficiency

is concrete. Next is the table space where plants can be grown in pots on tables above the ground layer to utilize more space. Lastly, some plants can be hung around the inside of the greenhouse if necessary.

Water Efficiency

The next part of the "Tips and Tricks" graphic gives the reader simple tricks to conserve water. Installing an automatic watering system is a very effective way to conserve water and keep track of water usage. Using drip irrigation is another effective way to cut down on water use; drip irrigation is known to be the least water intensive irrigation system. Next the guide gives a system to preserve water by collecting and reusing rainwater by contrasting a gutter system. Furthermore, a drainage system can be installed and excess water can be filtered an redistributed back into the greenhouse.

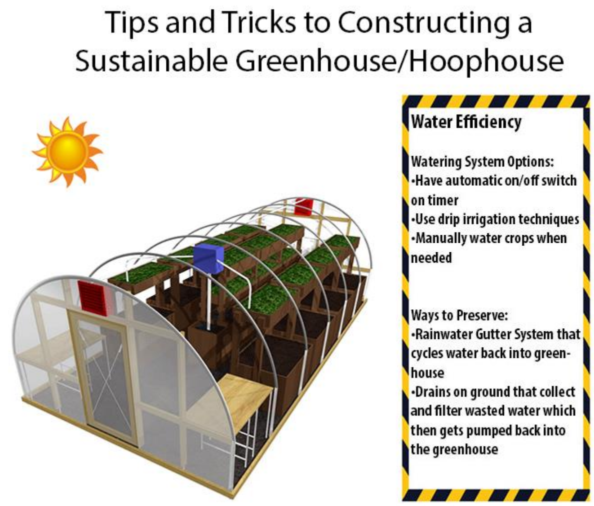


Figure 64: Tips and Tricks - Water Efficiency

Site Efficiency

The rollover of site efficiency tells the reader how to orient a greenhouse along with different shapes that capture the most sunlight. A huge mistake that many planters make when constructing is not paying attention to the direction which the greenhouse is orient. It is vital that your greenhouse be oriented with the largest glazing wall faces south. This insures that the plants receive the maximum amount of sunlight. The most common shapes for a greenhouse are even span, uneven span, modified arch, and Quonset. With the most effective shape being uneven span while a Quonset shape receives the least amount of solar radiation.

Figure 65: Tips and Tricks - Site Efficiency

Insulation

When constructing a greenhouse the most important aspect is insulation. A greenhouse that is highly insulated and can hold in heat is the least expensive to operate. There are a couple ways to insulate your greenhouse the first being to insulate the glazing material, with tools such as insulating curtains. Next, insulating around the ground creates a “thermal bubble” of warm soil heating the greenhouse from the ground. Constructing a greenhouse using material with high R-values is the most effective way to build an energy efficient greenhouse. Lastly, making sure a greenhouse is air tight by sealing any gaps is an easy way to make sure one is saving as much energy as possible.

Figure 66: Tips and Tricks - Insulation

Ventilation

Ventilation is important to think about when constructing a greenhouse to ensure there is a way too cool the structured during the hot summer days. There are two ways to ventilate a greenhouse. The first way is to ventilate it using passive technology that does not require power and the second is to use active technology that does require power. Exhaust vents are commonly found in greenhouses however this form of active ventilation is not ideal for a sustainable greenhouse. Automated vents in the top of the greenhouse are another form of active technology. However, this is a more viable option than the exhaust vents because they use less power and still have a profound impact in the greenhouses. The most sustainable option is to utilize natural convection currents by using technologies such as a trombe wall.

Figure 67: Tips and Tricks - Ventilation

Energy Source

The most common way to power a greenhouse is by using the power grind. However, recent sustainable efforts have taken advantage of renewable resources such as wind and solar power. The main disadvantage to using wind or solar power is that both usually have a limited lifespan and can therefore become expensive to implement. Fortunately the lifespan for both is usually long enough to make back the initial investment.

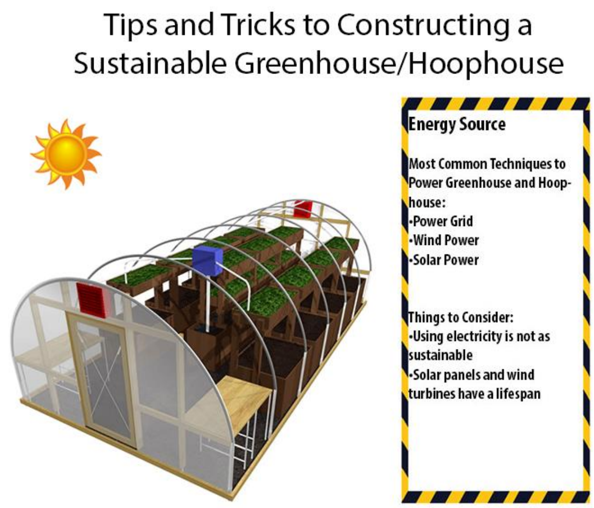


Figure 68: Tips and Tricks - Energy Source

4.3.3 "15 Easy Steps to Building Your Own Backyard Hoop House" Video

The team then created a how-to video walking viewers through a step-by-step construction of a Weatherguard round top commercial hoop house. This is the hoop house that the team constructed at the Tesuque Day School with their sponsor Tony Dorame, a few members of the Tesuque Environment Department, and several students from the Santa Fe Indian School. A transcript of the video is provided in Appendix D along with a complete listing of the video slide by slide.

5 Conclusions and Recommendations

From the team's research and experimental results several conclusions have been drawn about how to improve the Santa Fe Indian School and Tesuque greenhouses to make them more sustainable and energy efficient. Additionally, details of an ideal, low-cost, energy-efficient greenhouse for the Santa Fe, New Mexico area have been identified.

5.1 Recommendations for Santa Fe Indian School Greenhouse

After measuring and analyzing the SFIS greenhouse and testing different insulation retrofits, the team has determined several ways to help make the SFIS greenhouse more efficient. There are a few low cost, simple ways to improve the efficiency of the greenhouse. Easy fixes include sealing all small gaps with spray foam insulation and adding draft guards to the doorways. This will create an airtight system that won't allow the cold air in and warm air out. With more time and money, another suggestion is to create a mudroom around the doorways to eliminate the draft from the doorways. To do this, the back door should be taken out and replaced with a new sheet of corrugated polycarbonate, and then constructed into a mudroom coming off of the main door.

Additionally, adding insulation will greatly cut back on heater usage. From the retrofit experiments, the team realized the best retrofit includes a roof insulation and ground insulation. It is calculated that installation of a 2 ft knee wall would cost SFIS approximately $270. However, using Virtual Grower, it is estimated that there would be a 7.4% annual cost saving which comes to about $420 per year of savings. This means that the retrofit would pay for itself in almost half a year, eventually making $150 in the first year.

Adding bubble wrap to the roof is a cheap way to add roof insulation. The initial cost would be around $225. Bubble wrap will still let light through the roof while adding some shading, which is important in the hot sun of Santa Fe. Although this is a possible retrofit, it is not the best solution. As mentioned before, heat escaping through the roof, also known as thermal radiation to the sky, is a major source of heat loss. Installing a high efficiency energy curtain is a much better insulator. An energy curtain is retractable at the roof so it only covers the greenhouse at night to provide the proper insulation. This is much more expensive retrofit, but it would produce the best results.

While insulation is a key component of a sustainable, efficient greenhouse, thermal mass is equally as important. There are two main ways to add thermal mass to the SFIS greenhouse. As calculated before, it would take about 20, 55-gallon water barrels to compensate 1 hour of heater usage. The water barrels would collect the heat from the day and then slowly dissipate the heat overnight as the water inside cools. Water has a high specific heat which is the reason water barrels are an excellent form of thermal mass; this property allows water to hold huge amounts of heat. The second way to add thermal mass is to add a thermal bubble around the base of the greenhouse. Digging a trench around the outside of the greenhouse about 4 ft deep and adding Styrofoam insulation, would successfully create a thermal bubble and keep the greenhouse soil warm, thus providing warmth to the inside of the greenhouse. The second major heat loss is through the ground. Therefore, creating a thermal bubble underground around the outside of the greenhouse will help cut back this type of heat loss as well.

All of these retrofits will help cut back on heater usage, and therefore reduce the annual cost of operation. The less the heater is used, the more passive the greenhouse becomes. One easy fix is to use the sun to help heat up the greenhouse in the morning instead of the heaters. The team went to the SFIS greenhouse in the morning to assess the heater usage in the morning. When the greenhouse transitions from the set night time temperature (62°) to the day time temperature (72°), the two heaters continuously run for an additionally 1.33 hours to raise the inside temperature to the day time temperature. This is shown in Figure 69. The red circle is highlighting the time when the heaters are being utilize the raise the inside temperature. One major recommendation is to change the day temperature to begin later in the day so the sun can naturally heat the greenhouse to the set temperature instead of the heaters. Additionally, if the nighttime temperature didn't start until later in the night, this would cut back on the fan, vent, and swamp wall usage to cool the greenhouse. This is not as much of an inefficient process because the vent is run by solar panels. Overall, using the sun as the natural heater and cooler as it rises and sets is an essential way to make this greenhouse more sustainable.

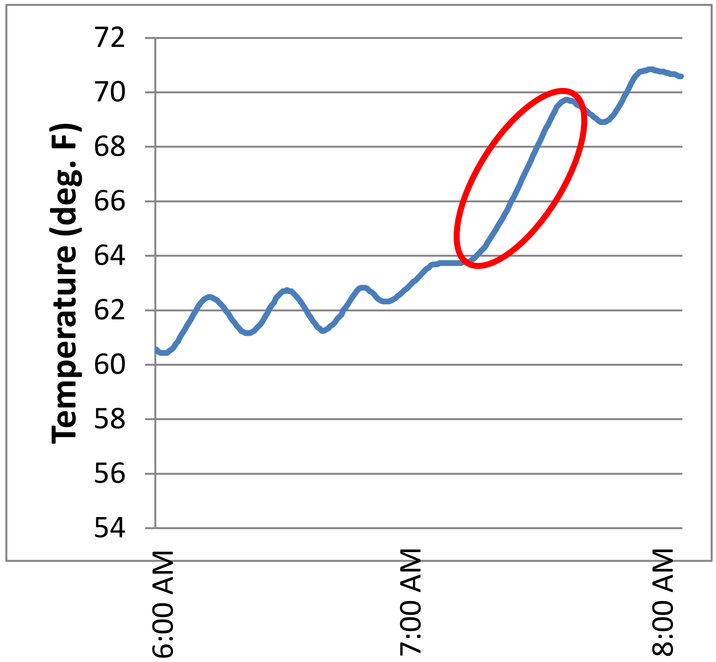


Figure 69: SFIS Transition from Night to Day

The final recommendation, if time and money were not an issue, is to completely reorient the greenhouse. Taking apart the greenhouse and reconstructing it with the main glazing wall facing due south would be beneficial. It would allow maximum sunlight into the greenhouse. If the greenhouse were reoriented, the other glazing walls would not be necessary. They could be covered with insulation or thermal mass. Right now, the cooling wall is the closest wall facing south. This cooling wall should be on the north side to provide cool air. The greenhouse can also be virtually oriented using the shading tarp on top of the roof. If the tarp was oriented so the quarter of the roof that is facing due south is exposed, then the greenhouse would be virtually oriented. However, the swamp wall will still be the main wall facing south and it greatly decreases the amount of sunlight let into the greenhouse.

To summarize the recommendations, the following are the different options to make the SFIS greenhouse more energy efficient and sustainable.

1. Seal all gaps using foam insulation and draft guards
2. Construct a mudroom, eliminating one door
3. Add Insulation:
    - 2 ft knee wall around perimeter
    - Bubble wrap roof
    - Energy curtain

4. Add thermal mass
    - 55 gallon Water barrels
    - Thermal bubble underground perimeter
5. Cut back on heater usage
    - Use sun as natural heater
    - Delay day and night temperature transition
6. Reorient Greenhouse or Virtually Orient Greenhouse

The only other recommendation to make is to keep monitoring the greenhouse using the HOBO U12 sensor. To fully understand the efficiency and improvement of the greenhouse once retrofits are installed, one must keep measuring. The goal is to make the greenhouse a year round greenhouse. The hope is that these retrofits will allow the greenhouse to be used year round for planting and educational purposes as well as to create a more sustainable, energy efficient greenhouse that can be used to teach the students about the potential of greenhouse farming which they could then bring to their own pueblos.

5.2 Recommendations for Tesuque Greenhouse

After measuring and analyzing the Tesuque greenhouse and testing different insulation retrofits, the team has determined several ways to increase the efficiency the Tesuque greenhouse. There are a few low cost, simple ways to improve the efficiency of the greenhouse. Easy fixes include adding draft guards to the doorways and adding material to seal the rips in the polyethylene or replacing the cover all together. This will create a more airtight system that won't allow the cold air in and warm air out. Replacing the glazing material would be worth the trouble and cost because it seems evident the UV rays have broken down the material over time. Polyethylene only has a life expectancy of about 4 years before it starts clouding and blocking out sunlight. Therefore, the covering should be completely replaced. For a higher efficiency, the polyethylene should be changed with a better material that will last longer, tear less, and have a higher insulating value.

Another way to decrease air leaks is to create a mudroom around the doorways to eliminate the draft from the doorways. To do this, the back door should be taken out and then constructed into a mudroom coming off of the main door.

Additionally, adding insulation will help cut back on heater usage greatly. From the retrofit experiments, the team realized the best retrofit includes a roof insulation and ground insulation. It is calculated that installation of a 2 ft knee wall would cost Tesuque approximately $230. However, using Virtual Grower, it is estimated that there would be a 6.3% annual cost savings, which comes to about $210 per year of savings. This means that the retrofit would pay for itself in a little over one year.

Adding bubble wrap to the roof is a cheap way to add roof insulation. The initial cost would be around $175. Bubble wrap will still let light through the roof while adding some shading, which is important due to the strong Santa Fe sun. Although this is a possible retrofit, it is not the best solution. As mentioned before, heat escaping through the roof also known as thermal radiation to the sky is a major source of heat loss. Installing a high efficiency energy curtain is a much better insulator. An energy curtain is retractable at the roof so it only covers the greenhouse at night to provide the proper insulation. This is much more expensive retrofit, but it would produce the best results.

While insulation is a key component of a sustainable, efficient greenhouse, thermal mass is equally as important. There are two main ways to add thermal mass to the Tesuque greenhouse. As calculated before, a 55-gallon water barrels gives off 460 Btu/°F. The more water barrels put in the greenhouse, the more heat they will produce to help maintain the inside temperature. The water barrels would collect the heat from the day and then slowly dissipate the heat overnight as the water inside cools. Water has a high specific heat, which means they can store a tremendous amount of heat, making water barrels an excellent form of thermal mass. The second way to add thermal mass is to add a thermal bubble around the base of the greenhouse. By digging a trench around the outside of the greenhouse about 4 ft deep and adding Styrofoam insulation, it would successfully create a thermal bubble and keep the greenhouse soil warm, thus providing warmth to the inside of the greenhouse. The second major heat loss is through the ground. Therefore, creating a thermal bubble underground around the outside of the greenhouse will help cut back on this type of heat loss.

All of these retrofits will help cut back on heater usage, and therefore reduce the annual cost of operation. The less the heater is used, the more passive the greenhouse becomes. Although the goal is to run the greenhouse without the need of the heater, the current state of the greenhouse will not be conducive for farming if the heater was not used at all. This can be seen in Figure 70. The thermostat is set to 60° yet the inside temperature drops to around 51°. The red lines on the graph show when the heater is on. Despite the fact that the heater turned on 6 times in an hour, the inside temperature still dropped about 10 degrees. This is a very significant amount and proves the inefficiency of the heater. This can be attributed to two possible causes. The first is that the thermostat is malfunctioning since the temperature leveled at around 50° that night. There is a possibility that the thermostat is just old and working improperly. Another possibility is that the heater has a safety feature and will not allow the heater to stay on for an extended period of time. Since the heater can't stay on long enough, it never produces enough heat to maintain the inside temperature. A major recommendation is to have the heater run for a longer period of time to maintain the inside temperature or purchase a new heater that will produce enough heat to combat the heat losses of the greenhouse. However, using the sun as the natural heater and cooler as it rises and sets is

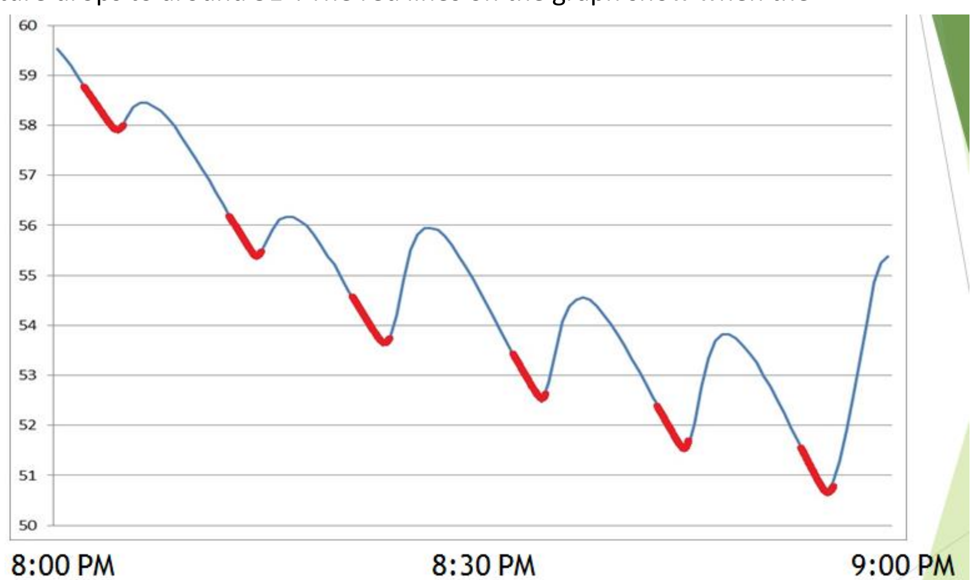


Figure 70: Tesuque Greenhouse Heater Usage

an essential way to make this greenhouse more sustainable. By adding insulation, thermal mass, and sealing the gaps, there is the potential that the greenhouse will not need to use a heater to maintain a proper inside temperature that is conducive for farming. This is the ultimate goal, creating a passive greenhouse.

The final recommendation if time and money were not an issue, is to completely reorient the greenhouse. Taking apart the greenhouse and reconstructing it with the main glazing wall facing due south would be beneficial. It would allow maximum sunlight into the greenhouse. If the greenhouse were reoriented, the other glazing walls would not be necessary. They could be covered with insulation or thermal mass. Right now, a wooden wall is the closest wall facing south. The greenhouse can also be virtually oriented using the shading tarp on top of the roof. If the tarp was oriented so the quarter of the roof that is facing due south is exposed, then the greenhouse would be virtually oriented. However, the wooden wall will still be the main wall facing south and it greatly decreases the amount of sunlight let into the greenhouse.

To summarize the recommendations, the following are the different options to make the SFIS greenhouse more energy efficient and sustainable.

1. Seal all gaps using material and draft guards
2. Replace Polyethylene
3. Construct a mudroom, eliminating one door
4. Add Insulation:
    - 2 ft knee wall around perimeter
    - Bubble wrap roof
    - Energy curtain
5. Add thermal mass
    - 55 gallon Water barrels
    - Thermal bubble underground perimeter
6. More efficient Heater
    - Use sun as natural heater
    - Have heater run longer
    - Replace heater
7. Reorient Greenhouse or Virtually Orient Greenhouse

The only other recommendation to make is to keep monitoring the greenhouse using the HOBO U12 sensor. To fully understand the efficiency and improvement of the greenhouse once retrofits are installed, one must keep measuring. The goal is to make the greenhouse a year round greenhouse. The hope is that these retrofits will allow the greenhouse to be used year round for planting as well as create a more sustainable, energy efficient greenhouse that can be used to teach the pueblo about the potential of greenhouse farming in their own backyards.

5.3 Proposal of an Ideal Greenhouse Design for Santa Fe

An ideal greenhouse for the Santa Fe area would be inexpensive to build and would require little to no energy to operate. It would provide all of the heat and light that the greenhouse needs using only the sun. It would maintain a moderate enough temperature to be used to grow crops year round. It would recycle moisture in the humid greenhouse air by returning it to the soil for the plants. Some greenhouses have been built elsewhere in the world that have similar sustainable characteristics. The task of this project team was to adapt existing sustainable, energy-efficient designs to the Santa Fe area, taking into account the climate and local materials that are available, among other factors.

5.3.1 Thermal Mass in the Ideal Greenhouse

It is essential to have high thermal mass in a greenhouse to achieve passive heating year round in the climate of the Santa Fe region. Additionally, this thermal mass should take advantage of the warm Earth temperatures a few feet below the ground by making the thermal mass below ground rather than above ground. The R-20 extruded polystyrene insulation surrounding the perimeter of a Synergistic Building Technologies greenhouse, which was modeled in this design, goes down four feet and achieves a temperature difference of 9°F between the soil under the greenhouse at a depth of four feet and the soil outside the greenhouse at a depth of four feet.[72] "Installing insulation around the perimeter of a building between wall insulation and four feet below grade effectively *couples* the structure to deep earth beneath the footprint of the structure. Equally important, it *decouples* the structure from the surface of the earth immediately surrounding the structure, thereby isolating the building from soil whose temperatures vary substantially from season to season."[73]

The team proposes that a similar thermal bubble of warm soil be achieved using a four foot deep underground perimeter wall of a different kind of R-20 insulation. Specifically, rather than use the R-20 extruded polystyrene insulation, people in Santa Fe can use 30 inch thick used tire bales, which have the same R-20 insulating value as the extruded polystyrene insulation. Used tires are used at the Tesuque Pueblo Seed Bank in the walls in the basement beneath the ground to provide insulation and may be a cheaper alternative than extruded polystyrene that is just as effective at turning a large amount of soil beneath the greenhouse into thermal mass.

Also note that adobe, the material to be used to build the walls of the greenhouse, also functions as a decent thermal mass. The specific heat of adobe is approximately 0.20 BTU/(lb*°F).[74] The specific heat of adobe in terms of BTU/(55-gallon-barrel*°F) can be calculated using the fact that the density of adobe is about 1600 kg/m^3.[75] The calculation is shown below:

$$Specific\ Heat\ Adobe\ = 0.20\ \frac{BTU}{lb\ °F}$$

[72] Kinney, L, J Hutson, M Stiles, and G Clute. "Energy-Efficient Greenhouse Breakthrough." American Council for an Energy-Efficient Economy. www.aceee.org/files/proceedings/2012/data/papers/0193-000414.pdf.
[73] Kinney, L, J Hutson, M Stiles, and G Clute. "Energy-Efficient Greenhouse Breakthrough." American Council for an Energy-Efficient Economy. www.aceee.org/files/proceedings/2012/data/papers/0193-000414.pdf.
[74] Wilson, Quentin. "Adobe as Mass." Quentin Wilson Adobe Resource. http://www.quentinwilson.com/adobe-as-mass/.
[75] Heathcote, Kevan. "Mud Brick (Adobe) Construction." Engineers Without Borders. www.ewb.org.au/resources/download/1918P2011-08-04_12:35:50/1L.

$$= 0.20\,\frac{BTU}{lb\,°F} * \frac{2.2\,lb}{1\,kg} *\ 1600\,\frac{kg}{m^3} * \frac{1\,m^3}{264\,gallons} * \frac{55\,gallons}{1\,Barrel} = \mathbf{147}\,\frac{\boldsymbol{BTU}}{\boldsymbol{Barrel} * \boldsymbol{°F}}$$

This means that 147 BTUs of energy is released by a 55-gallon barrel worth of adobe for each degree Fahrenheit that the adobe drops in temperature. Putting the specific heat of adobe into these units is useful because it allows us to determine the effectiveness of adobe as a thermal mass compared to water, the best thermal mass among all common materials:

$$\frac{Specific\ Heat\ Adobe}{Specific\ Heat\ Water} = \frac{147\,\frac{BTU}{Barrel*°F}}{458\,\frac{BTU}{Barrel*°F}} = 0.32$$

While a specific heat that is only one third of the specific heat of water may not seem substantial, for comparison, the specific heat of air is only about 24% of the specific heat of water. Of course, the main benefit of the adobe walls will not be that they act as thermal mass themselves, but rather that they will help transform all of the soil beneath the greenhouse into thermal mass and also that they will provide insulation between the inside and outside air.

5.3.2 Insulation in the Ideal Greenhouse

The amount of glazing material in a greenhouse should be minimized because glazing materials are poor insulators. The north, east, and west walls of an energy-efficient greenhouse should be made with an insulating material of R-20 or greater. In the Synergistic research greenhouse the non-glazing surfaces of the walls and ceiling of the greenhouse averaged R-35.[76]

The team proposes that the walls of an energy-efficient greenhouse in the Santa Fe area be made using adobe with straw bale insulation on the inside. While adobe is not as good of an insulator as many other materials, a high R-value can be achieved if one makes the adobe wall thick enough. Straw insulation is about R-2.38 per inch and adobe is about R-1.5 per inch. Therefore, a wall that is 18 inches thick, with 12 inches of straw on the inside and 6 inches of adobe would have an R-value of about 37.56. This is approximately what the make-up of the wall at the Tesuque Pueblo Seed Bank is in terms of material, dimensions, and R-value. The wall of the Tesuque Pueblo Seed Bank can be seen in Figure 71.

Figure 71: The 18 inch thick adobe wall of the Tesuque Pueblo Seed Bank as seen from the inside, with a square cut out showing the straw insulation on the inside of the wall.

Adobe is also a superior alternative to the Styrofoam insulation because of cost. In the Santa Fe region, material costs of adobe are essentially zero, whereas the cost of R-20 extruded polystyrene insulation is about $66.25 for a 4ft by 8ft sheet that is 4 inches thick.[77] While the labor costs for

[76] *Ibid*.

[77] "4" x 4' x 8' R20 FOAMULAR 250 Rigid Foam Insulation." Menards. http://www.menards.com/main/building-materials/insulation/panels/4-x-4-x-8-r20-foamular-250-rigid-foam-insulation/p-1384813-c-5779.htm.

adobe may be greater than the extruded polystyrene insulation, it should be noted that the adobe itself is the structural material to build the greenhouse. On the other hand, when extruded polystyrene Styrofoam sheets are used for insulation it is necessary to construct an additional structure for the greenhouse using a different material that can hold the Styrofoam. Therefore, on the whole, the cost of using adobe would be much less than using extruded polystyrene as Larry Kinney did. According to the Director of the Tesuque Department of Agricultural Resources, Emigdio Ballon, the Tesuque Pueblo Seed Bank, which has 18 inch thick adobe walls, as shown in Figure 71, cost only $10,000 to build.

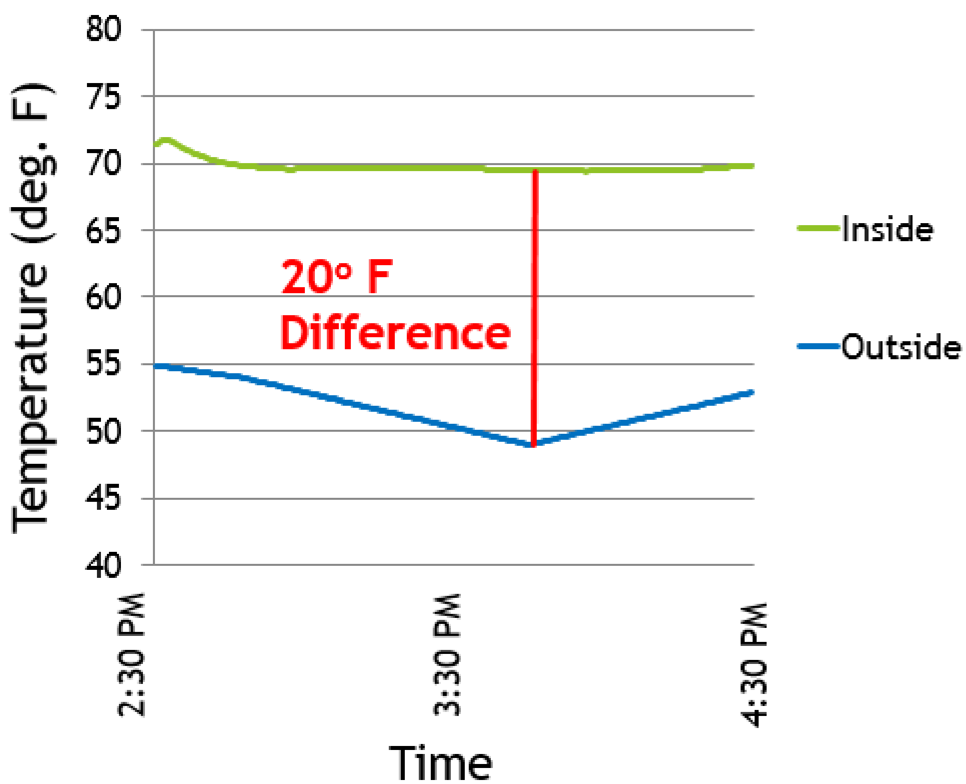


Figure 72: A graph of the temperature on the inside and outside of the Tesuque Pueblo Seed Bank for a two hour period during late afternoon, showing that the inside temperature can be maintained well above the outside temperature without any active heating.

As can be seen in Figure 72 above, the temperature on the inside of the Tesuque Pueblo Seed Bank stayed at a constant 70°F for a two hour period despite the fact that it was only 50°F to 55°F outside during the same period, thus demonstrating the effectiveness of the straw and adobe insulating walls of the Seed Bank. Larry Kinney's Synergistic Building Technologies research greenhouse in Colorado uses only the sun to provide all of the heat and lighting that it needs to operate year round, and a greenhouse in Santa Fe could do the same by mimicking Kinney's greenhouse's R-35 walls using adobe and straw insulation.[78] This would allow for heating costs to be eliminated as no gas heater or other powered heat source would be needed.

5.3.3 Recycling Moisture and Heat in the Ideal Greenhouse

Larry Kinney's team developed a "'Greenhouse Earth Thermal Storage' (GETS) system that pulls warm air from the top of the greenhouse through drainage pipes in the earth underneath." This transfers moisture from the humid air into the ground for use by the plants, essentially watering them from underneath. This is a very sustainable feature because the water is recycled. Alternative ways of dealing with humidity often involve venting the humid air out of the greenhouse, but releasing the humid air outside just wastes the moisture. The Greenhouse Earth Thermal Storage (GETS) system also takes heat from the hot air at the top of the greenhouse when the sun is shining and adds it to the soil, which helps to cool the greenhouse air in the summer. In Larry Kinney's greenhouse the GETS system helped prevent the air from ever going above 90°F at any point during the entire summer.[79] Also, on sunny days in the winter the air at the top of greenhouse can become too humid and hot. The GETS system also functions very well in the winter because it recycles the heat from the top of the greenhouse back into the soil rather than expel it outside, like other greenhouses sometimes have to do to deal with the high humidity. In the Santa Fe area, where water is especially scarce, recycling water like this is an essential aspect of creating a sustainable, water-efficient greenhouse.

Figure 73: "Two Greenhouse Earth Storage Systems (GETS) installed, vertical rigid R-10 Styrofoam in place. A second R-10 sheet was installed, then horizontal R-10 sloped gently downward 2.5 feet below surface."

[78] Kinney, Larry. "Greenhouses." Synergistic Building Technologies, Inc. http://www.synergisticbuildingtechnologies.com/greenhouses.html.

[79] Kinney, L, J Hutson, M Stiles, and G Clute. "Energy-Efficient Greenhouse Breakthrough." American Council for an Energy-Efficient Economy. www.aceee.org/files/proceedings/2012/data/papers/0193-000414.pdf.

As can be seen in Figure 73, a Greenhouse Earth Thermal Storage system has a fan that pulls hot, humid air from the top of a greenhouse into drainage pipes beneath the ground.[80] The water condenses in these pipes, which are gently sloped downwards across the greenhouse. The pipes in the GETS system were designed for drainage systems. They have holes to allow the condensed water to drain out, as well as nylon "sock" material that prevents dirt, worms, and other critters from getting into the pipes. The condensed water drains out and cool dry air emerges at ground level.[81]

5.3.4 Other Considerations for an Ideal Greenhouse

As has been mentioned elsewhere in this paper, there are other factors that go into making an ideal, sustainable, energy-efficient greenhouse. For example, it is important that the greenhouse be made as airtight as possible to prevent heat loss.

As was mentioned in the Background, it is also important that the greenhouse's glazing wall face due south so that it can obtain the maximum amount of sunlight, especially in the winter months. Since the one glazing wall on the south side of the greenhouse is not even made completely of glazing material, but rather has some insulation and some windows, it is important to maximize the amount of sunlight that goes through the windows. This is accomplished by installing a row of light shelves along the south wall of the greenhouse beneath the windows. The light shelves reflect additional sunlight in through the windows. Lastly, the walls inside of the greenhouse are made reflective. This makes it so that rather than be absorbed in the walls on the North side of the greenhouse, the sunlight bounces around and strikes the plants helping them to grow. Larry Kinney's greenhouses only have a few windows to allow light in, yet the plants inside his greenhouses receive sufficient sunlight due to the use of light shelves and reflective surfaces on the inside of the greenhouse.[82]

Finally, insulating shutters should be employed in the greenhouse to cover the glazing windows at night. It would require very little electricity to make these insulating shutters open and close automatically, which is why Larry Kinney chose to automate them in his very efficient sustainable greenhouse in Colorado. However, if one wishes to only have a manual system to open and close them that would work too, so long as there is always someone around to close them at night and open them in the morning.

[80] Kinney, Larry. "Energy-Efficient Greenhouses: The New Frontier." Energy Star Summit. energystarsummit.org/sites/default/files/session/82758/closekinneylarry.pdf.
[81] Kinney, Larry. "Energy-Efficient Greenhouses: The New Frontier." Energy Star Summit. energystarsummit.org/sites/default/files/session/82758/closekinneylarry.pdf.
[82] Kinney, L, J Hutson, M Stiles, and G Clute. "Energy-Efficient Greenhouse Breakthrough." American Council for an Energy-Efficient Economy. www.aceee.org/files/proceedings/2012/data/papers/0193-000414.pdf.

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Appendix A

Survey that will be available to farmers and companies with greenhouses

Greenhouse/Hoop House Questionnaire:

- How long have you been using your greenhouse?
- Would you consider it to be efficient? Why?
- What sustainable technology, if any, does your greenhouse have? (i.e. insulated shutters, temperature/humidity gauges, etc.)
- What type of power source does it run on?
- How do you heat it? Cool it?
- What is the cost to operate and maintain your greenhouse?
- How many crops do you grow in your greenhouse?
- What kinds of crops do you grow?
- If one improvement could be made to your current greenhouse, what would it be? Why?
- How much would you pay for a greenhouse that would allow you to farm year-round?
- Other comments/thoughts?

Appendix B

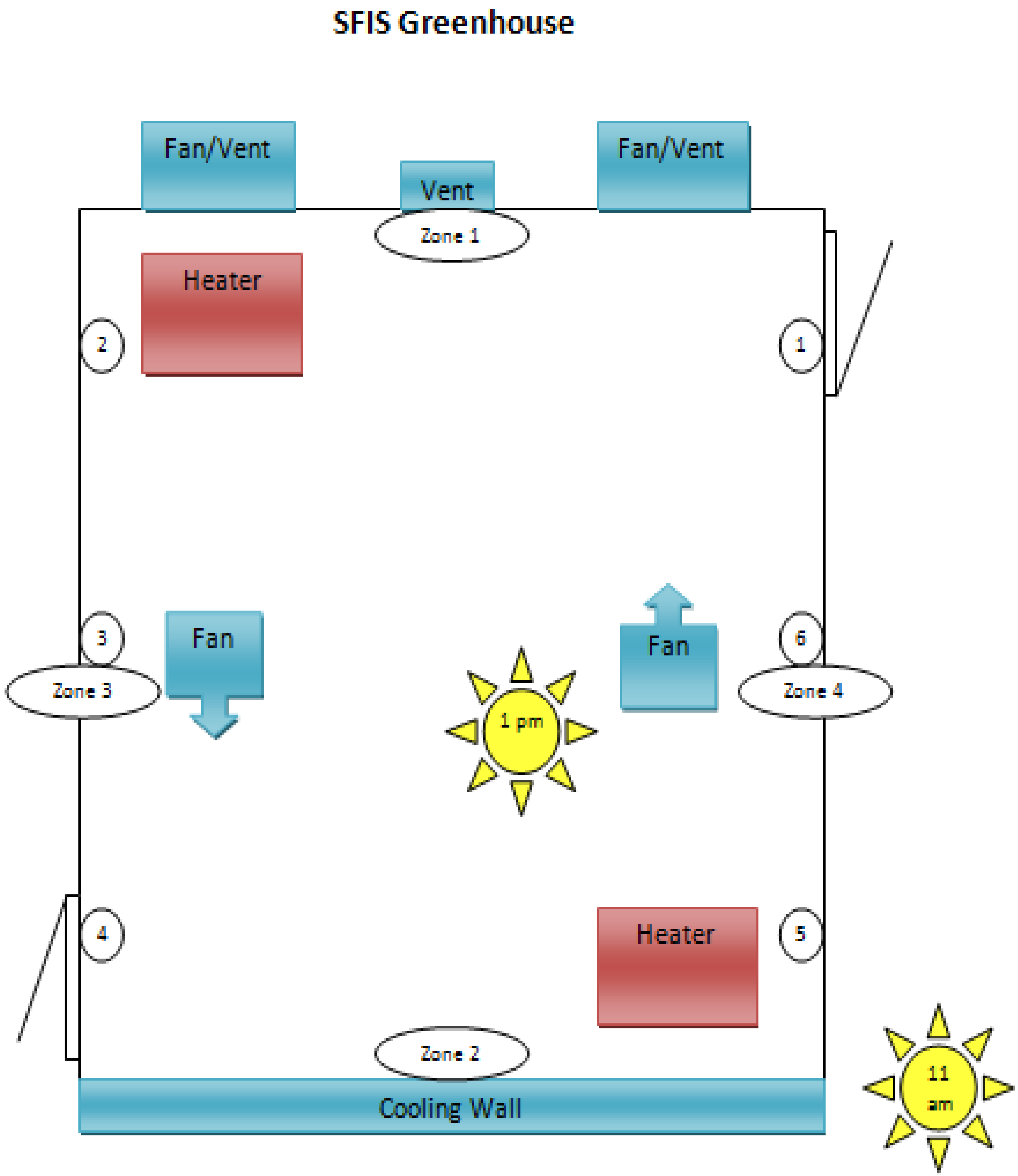
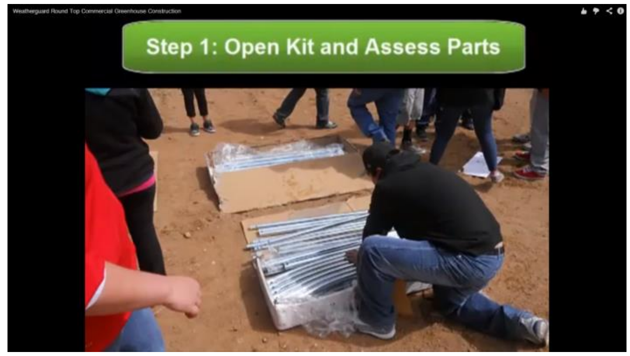


Figure 74: SFIS Thermometer and Sensor Placements

Appendix C

How To Video Slideshow




Step 4: Fastening Arches


Step 4: Fastening Arches


Step 5: Stand Arches Upright


Step 5: Assemble Support Beams


Step 5: Assemble Support Beams


Closer Look


Step 5: Assembling Support Beam


Step 6: Adding Feet


Closer Look


Step 7: Adding Support
Beams to Base

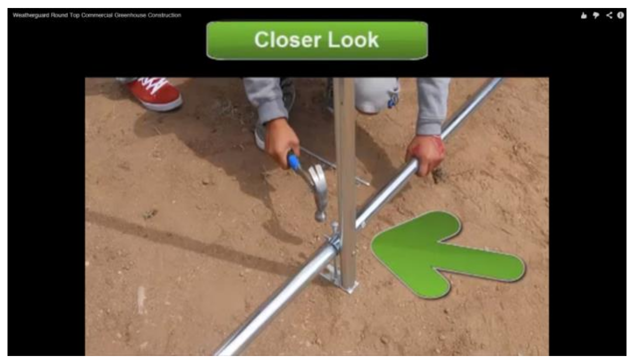

Step 7: Adding Support Beams
to Base


Step 8: Fasten Feet to Arches


Recap: 5 Support Beams Assembled


Step 9: Orient HoopHouse Properly


Step 10: Secure HoopHouse to Ground


Closer Look


Step 11: Lay Out Plastic Covering


Step 11: Lay Out Plastic Covering


Step 11: Lay Out Plastic Covering


Step 12: Attach The Ends


Step 12: Attach The Ends


Step 13: Add Main Covering

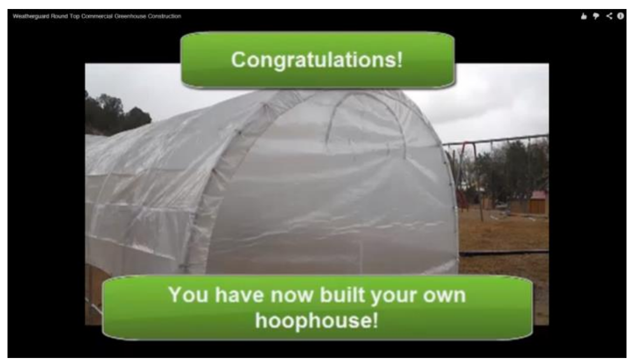

Step 13: Add Main Covering

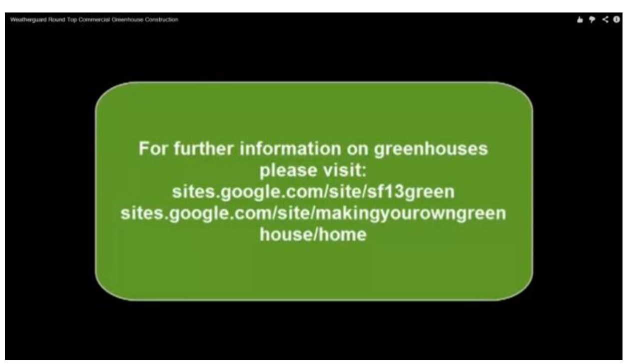

Step 13: Add Main Covering


Step 14: Install Ratchets To 4 Corners


Step 14: Install Ratchets To 4 Corners
Add Straps


Step 15: Tie Down Covering


Congratulations!
You have now built your own hoophouse!


For further information on greenhouses please visit:
sites.google.com/site/sf13green
sites.google.com/site/makingyourowngreenhouse/home

Appendix D

Transcript of How To Video

Hello and welcome to 15 easy steps to building your own backyard hoop house in this short video well show you just how easy it is to grow crops in your back yard.

To begin this process open your kit and assess all the parts to make sure you have everything provided to you in the instructions.

To begin the construction by assembling all the parts labeled A and B there should be four arch pieces to construct one complete arch and 6 arches total in the Skelton of your greenhouse.

In order to assemble the arch pieces simply insert the male end into the female end of another arch. Once you have assembled all of your arches lay them on the ground so you can fasten them together.

To fasten the arches simply insert the bolt into the joint using a bolt provided in the kit.

As you can see from this closer look the bolts are longer then they need to be but we'll discuss this in a moment.

To continue fasten all of the arches together once you have done that you can stand all the arches up right and begin constructing the rest of your skeleton.

To fasten the arches together you want to use the horizontal supports labeled part d in your kit.

In order to fasten the horizontal supports you want to insert the joint of the bean into the extended portion of the bolt from your arch.

As you can see from this closer look the bolt seems to fit much better now that you have your horizontal supports in place.

And taking a look at the whole greenhouse now you see there are three sections with horizontal supports.

So step six you want to add the feet to the greenhouse so that it will be planted into the ground.

As you see here the feet fasten just the same as all the other parts.

Once you have the feet fastened into your arches you want to assemble more horizontal supports at the base of the hoop house.

These are fastened just the same as the others using the long bolts provided by your kit.

Once the base is assembled to the horizontal support you want to fasten the feet to the arches.

Congratulation you've constructed your entire hoop house skeleton and now your ready to orient it the correct way.

In order to orient your hoop house simply move it so that the largest glazing wall in the hoop house faces due south that way it receives the most light during the day.

Once you have it in the proper locations you need to buy steaks to secure it to the ground.

And here's a closer look in how you secure it to the ground, just use a few steaks and hammer it into the dirt.

Once your greenhouse is secure you want to lie out the plastic covering that will then be used.

As you can see there are two end pieces one with a door and one without.

As well as one large piece of plastic to cover over the top.

Once you have all the plastic laid out you want to assemble the two ends using the bungees from your kit.

As you can see here it's fairly simple to construct just using the two bungees.

Once your two ends are attached you want to lay the main covering over the top of your hoop house and you want to extend the main cover over the front as you see here so there is not much of a draft when the wind picks up at night.

Once your main cover is on you want to install ratchets onto four corners of your hoop house.

From there you take straps which are provided inside the main covering and feed them through the ratchets and tighten down the air covering from there you use string provided in the kit to tie down the rest of the covering.

And congratulations you have now built your own hoop house and are now ready to start growing in your own backyard.